# TOWARDS SMART CITY MODELS: EVALUATION OF METHODS AND PERFORMANCE INDEXES FOR THE SMART URBAN CONTEXTS DEVELOPMENT

**Doctor of Philosophy (PhD) in Energy and Environment**
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# ABSTRACT

Today, cities are facing many challenges such as pollution, resource consumption, gas emissions and social inequality. Many future city views have been developed to solve these issues such as the Smart City model. In literature several methods have been proposed to plan a Smart city, but, only a few of them have been really applied to the urban context. Most of them are indeed theoretical and qualitative approaches, providing scenarios that have not been applied to real universities campus/cities/districts. In this framework, the aim of this thesis is to integrate a previous qualitative smart method and transform it into a quantitative and ex-post one. The feasibility and validity of the method will be tested through the comparison with another existing model and the application of both approaches on two real case studies, characterized by different territorial levels. Finally, the flexibility of this new quantitative smart methodology is demonstrated throughout its application on another two urban contexts: highland villages and the Italian suburb. Results of the analysis show that this smart methods is reliable and provide coherent results, becoming an useful instrument for designers and planners for the identification of the most performing Smart strategies.

# INTRODUCTION

Starting from the Greek era, cities have been the core of the human's skills and cultural evolution. Nowadays, towns and metropolises still occupy an essential role in facing the challenges of global urbanization, evolving its capacity to respond to the citizen's needs. Among the global challenges, the climate issue is rapidly forcing authorities and governments to provide sustainable and efficient solutions. In this framework, the importance of shifting from traditional urban planning to more inclusive and innovative ones is an urgent request. As a consequence, the Smart City concept was developed as a reliable key to the contemporary cities' requalification.

Over the past decades, there has been an evident passage from a Smart City focused on technology's network (strongly related to the Information and Communication Technologies-ICTs) able to provide an efficient urban infrastructure (i.e., transport, communications, energy, etc.) to a more global approach, moving its attention to human needs. This contemporary definition gives a central role to the life quality of citizens, finding a balanced relationship between hardware and software tools.

This evolution of the Smart City's interpretation was followed by local and international governments, providing incentives and funding for the application of this model in different territorial levels. In the European vision, this concept is also increasing its power and magnitude as the latest regulation underlines (ISO 37122:2019). This ISO standard proposes methodologies and indicators to measure the performance of the Smart cities. Moreover, a general and inclusive definition of the Smart cities was finally proposed:

*"A city that increases the pace at which it provides social, economic and environmental sustainability outcomes and responds to challenges such as climate change, rapid population growth, and political and economic instability by fundamentally improving how it engages society, applies collaborative leadership methods, works across disciplines and city systems, and uses data information and modern technologies to deliver better services and quality of life to those in the city (residents, businesses,*

*visitors), now and for the foreseeable future, without the unfair disadvantage of others or degradation of the natural environment".*

Many Smart City projects were therefore carried out due to the exploiting of this innovative urban planning model. Some international teams were focused on the elaboration of smart approaches, as a result of a mix of theoretical principals and peculiar technological tools. Although the variety of the Smart models and methodologies exposed in  literature, few of them provided the designers and planners with tangible and scalable methods, applicable to different territorial levels.

To cover this gap, this thesis presents a useful and reliable answer, investigating the relevance of a Smart Methodology that can guide the transformation from a model to a smart one.

First, an existing qualitative smart approach is described and integrated in this work, focusing its application on a university's campus. This method, named the Incidence Matrix Method (IMM), was previously developed by a team of researchers from Sapienza, University of Rome. Laying its foundation on a global and inclusive characterization of a smart model, it is composed of different steps, wherein an important integration was done in this thesis. Then, this method will be completely transformed into a quantitative and ex-post one to overcome its subjectivity that characterizes a qualitative scheme. To test its efficiency and reliability, a comparison with another smart approach was performed. Finally, the flexibility of this new quantitative smart methodology is demonstrated throughout its application on two urban contexts: highland villages and the Italian suburb.

This dissertation is divided into 6 sections which proceed with the following line: introduction, integration of the IMM approach and its application to a university campus, description of the new methodology named Quantitative Incidence Matrix Method (QIMM), application of this methodology to different contexts (Smart highland communities, Smart Suburb) and conclusions.

More in details, Chapter 1 presents the IMM scheme and each phase of its analysis, focusing on the elaboration of a set of performance indicators able to describe the complexity of the university's campus. Therefore, the step of the indexes standardization was deeply analyzed, proposing different calculation method for correctly standardize them. The application to a real campus showed how the smart method can evaluate the impact of the proposed solutions to each smart axis, providing a global view of the campus to the designers.

Chapter 2 represents the core of this thesis, wherein the author transforms the IMM approach into a quantitative one, overcoming some subjected weights that could affect the entire process. To successfully do that, this approach, named Quantitative Incidence Matrix Method (QIMM), was compared with another method presented in the literature. In parallel, both approaches were applied to two case studies, an isolated building and district ones. Conclusions highlighted the weakness and the strengths of both smart approaches, but in general, they provided similar results, attesting their reliability and giving suggestions for future developments.

Starting from the validation of the QIMM approach, Chapter 3 describes its application to a complex case study, an energy microgrid for six highland villages in Italy. Moreover, the resilience theme was included in this analysis, in term of energy resilient plants. Energy systems must face with failures or blackout during its operation time , which can provoke consistent damages. A set of resilient and smart indicators were therefore elaborated. Results underlined the best resilient scenario which obtained a good performance for most of the smart axis.

In Chapter 4 the Smart project is focused on the urban periphery, considered as a neglected settlement of the contemporaneous cities. Applying the QIMM approaches, this work pointed out the importance of citizen's opinions. In line with this, a survey was given to citizens to understand which services they would prefer in the project area. A multifunctional centre was defined as an optimal and smart strategy for enhancing this suburb.

# Chapter 1

# FROM SMART CITY TO SMART CAMPUS: application of a Smart Method for the development of a Smart University Campus

## 1.1 Introduction

Currently, the complexity of the university system is well known and articulated: the administration of resources, the organization of various activities, the education of new minds. This system frequently comes up against considerable problems and requires innovative and multifunctional approaches to cope with these issues. In this context, the Smart concept can be applied to overcome current difficulties. This model is based on a deep knowledge of the interested area, followed by the identification of specific and focused actions. Developed during the last years, the concept of Smart City lays its foundations on the studies made by the University of Vienna. The model has the aim to draw up an evaluation ranking of several European examined cities. The model of Smart City moves along six axes (Smart Economy, Smart Governance, Smart People, Smart Environment and Smart Living); each of them contains a different parameter for the evaluation of the level of smartness of the cities.

## 1.2 State of art: from Smart City to Smart Campus projects

Keeping in mind, that a consistent review of the models and approaches of the Smart City concept was done in the second chapters of the thesis, in this paragraph the focus is to briefly describe the Smart City concept to underline its connection to the Smart Campus one.

Many projects have been developed based on the Smart City model. This theme, therefore, evolved during the last 30 years, changing its criteria depending on the type of the researcher's approaches.

In [1] a common system for evaluating Austrian cities of any size and type is developed, promoting the creation of innovative and interconnected solutions; another example is the study which indicates a set of performance indicators, focused on climate change and energy efficiency [2]. Researches, especially the one concerning the definition of performance indicators have been developed for assessing specific macro areas: environment, sustainability and energy. The same processes and dynamics of cities can be also found in University campuses, allowing to apply the same Smart model to this urban microcosm. Many frameworks of Smart Campus have been elaborated by international teams, such as the improvement of campus energy efficiency proposed by an Italian team [3], the development of technological platforms able to manage and promote the environmental and buildings sustainability [4] [5], the creation of p sustainable and accessible services for users [6]. Among this, several types of research are focused on the development of cloud platform services as it is exposed to the work of [7]. The authors proposed an innovative platform named "Smart Campus Central Intelligence – SCCI", that allows managing data and service that they have to be sensible, accessible, social and visible.

Regarding recent works, only a few papers present application and description of the real smart campus. An example is a work of [8], in which the authors enhanced their smart project at the University of Toulouse III Paul Sabatier, in France. In line with this, another study [9] recommended an IoT and cloud computing for the Wuhan University of Technology smart campus (China). Similarly in [10], the role of cloud computing and IoT is well promoted as a key tool for transforming a campus into an intelligent and innovative one.

As for Smart City, even for the Smart Campus, there are not complete models that analyze the problem from a global perspective. This brief investigation in literature highlights that also the latest projects are just focused on some areas, such as environmental, energy, informational (IoT and cloud computing) or administrative.

## 1.3 Aims and Methodology

In this framework, this study wants to adopt and integrate a methodological approach, named Incidence Matrix Method (IMM) [11], applicable to each university, but also flexible to the specific characteristics of each site under examination. Nevertheless, this methodology needs to be provided with certain tools able to direct the transformation of a university system into a Smart complex. In the applied methodology, an important phase consists of the creation and analysis of performance indicators, able to describe each macro area in a complete and exhaustive way. This phase will be investigated by the author aiming to show a possible scenario of Composite Indicators for each Smart field, which fully describes every aspect of the university campus, in a global view. The standardization and aggregation methods are chosen specifically for this study as it will be described in the following paragraphs. Moreover, these indicators are flexible enough to be adapted to other universities and to provide an accurate analysis of their current state.
Summarizing, this work aims to:

- Describe the smart methodology IMM (Incidence Matrix Method), based on the smart approach elaborated by the work of [11].
- Integrate the IMM process to propose a set of Composite Indicators and to identify a quantitative method to standardize them.
- Apply the integrated smart approach on a real case study (Sapienza, university campus).

## 1.4 Description of the smart methodology (IMM)

The Incidence Matrix Method (IMM) is composed by five steps: preliminary planning, identification of fields of action, data acquisition, data analysis, the definition of the strategies [12], [13].

The preliminary analysis is required to get a first idea of the intervention area, the users and the purpose and the feasibility of the project. More accurate is the analysis of the project, more detailed and focused will be the final solutions developed. Stakeholders, citizens, politicians are all involved in these preliminary steps, since their needs and perspectives are crucial for smart planning. Moreover, this phase is essential for pointing out the particular characteristics of an urban settlement. Several characteristics of territorial levels have to be taken into account: the history and the evolution of the area, the geographical position and the surroundings, the cultural identity, the relation among the different parts of the city. The role of the urban planner is to outline a specific and all-embracing framework of the area through an integrated and multilayer analysis approach. According to this, the urban planner should be equipped with several tools able to give realistic simulations to highlight the existing relations among the urban elements and the consequent morphological effects of the interventions on the entire context.

The second phase aims to identify the Smart areas, the fields of analysis and action. The Smart fields defined in [14], have been adapted to the university campus, and transformed into five areas (Energy, Economy, Environment, Mobility, Living the campus), as showed in Figure 1. The reduction of the six smart axes into five was done by the author, following the previous works of the same team [13]. The "Governance" field is not considered as an isolated aspect, but it is integrated inside each axis; the Smart Living and Smart people axis are combined in one field, called "Living the campus" since the Living has been considered as the services supplied by the campus to the different user/people. Finally, the "Energy" field has been separated from the Environment, because it is better to highlight the impact of those two fields separately. This phase is important for the evaluation of the performance of the campus and the management of its development.

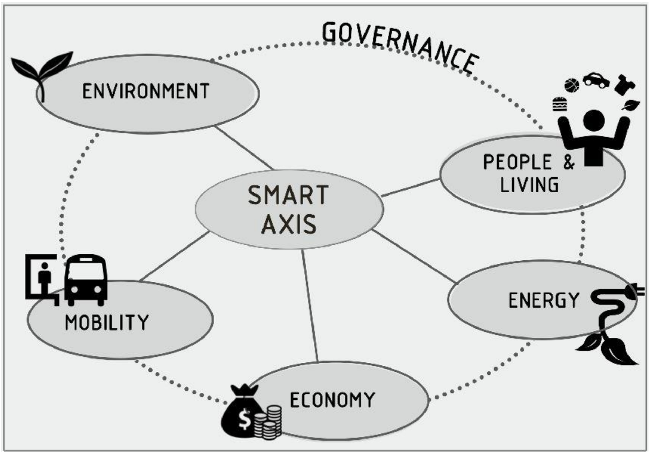


Figure 1: Smart axes definition

The third phase is regarding the data collection and it is composed by the acquisition of a large amount of information to be organized and placed in a database, where the information is transparent and shared among the involved stakeholders and partners. The researches, measurement campaigns and surveys are therefore essential to acquire data and information for the development of this database and the performance indicators, as it is exposed in the next paragraphs. The main problems in the data collection are usually the identification of information effectively useful and the difficulty in accessing data. For these reasons, the selection of the information depends not only on the purpose of the project but also on their accessibility, availability and relevance.

The fourth phase foresees the analysis of all available data, their standardization, aggregation and weighting, by using composite indicators (CI) for evaluating the points of strength and weakness of the context. Indicators are essential to collect data of the model and they are grouped inside the smart axis. It is not easy to combine all the variables, due to the big amount of information and their different peculiarities. Therefore, a good solution is to aggregate in a weighted manner the obtained data into different indicators, named Composite Indicator (CI), based on an underlying model of the multi-dimensional concept that is being measured [15].

The last phase proposes planning strategies to overcome the problems related to each field, highlighted by the values of the indicators.
Applying this model, according to this, the chosen strategies are efficient and integrated because they provide transversal solutions generating holistic benefits from all the points of view [16], [17].

More in details, a set of strategies were defined at the end of the process able to face the problems underlying previously. These actions represent an example of smart solutions that could be applied to the analysed context:: the amount and the typology of actions can be modified since this smart approach is flexible and scalable. Moreover, the categorization of those solutions is essential to establish the impact of them on each smart axis.

A decisional matrix (actions x fields) will be defined, named Incidence Matrix, for each smart axis, in which all the solutions are evaluated through specific "score" and "weight"(Table 1).

The actions are given a score comprised between -5 and 5, based on their level of synergy with the other actions. The sum of all these scores is the final score that represents the global impact of each strategy on each smart field. Then, a qualitative prioritization process has been developed based on the assignment of three additional scores which have been added to the final score each action.

The stakeholder's Score (SS), based on the number of benefits for the highest number of different stakeholders, such as users and companies; the Feasibility Score (FS), based on the level of the feasibility of the action; the Time Score (TS), based on the completion time required by each action. The role of those three weights is to give a priority to the actions, avoiding the equal final score of the strategies.

Table 1: Example of Incidence Matrix process

| **AXIS** | **ENVIRONMENT** | | | |
|---|---|---|---|---|
| | **Strategies** | | | |
| | Waste | Air quality | Landscape | Water |
| | **Actions** | | | |
| | ACTION 1 | ACTION 2 | ACTION 3 | ACTION 4 |
| EN | - | - | - | - |
| | [score] | [score] | [score] | [score] |
| ENV | - | - | - | - |
| | [score] | [score] | [score] | [score] |
| EC | - | - | - | - |
| | [score] | [score] | [score] | [score] |
| MOB | - | - | - | - |
| | [score] | [score] | [score] | [score] |
| LIV | - | - | - | - |
| | [score] | [score] | [score] | [score] |
| Score | …. | …. | …. | …. |
| SS | …. | …. | …. | …. |
| FS | …. | …. | …. | …. |
| TS | …. | …. | …. | …. |
| TOT | …. | Winner one | …. | …. |

Before implementing the strategies, the quantitative simulation of the actions will be performed. Many software can be used for the assessment of Smart performance. The base requirement of the software is the possibility of simulating the different type of smart solutions, not only the energy or environmental ones.

## 1.5 Integration of the IMM methodology: focus on the PIs analysis and their standardization

It is evident that the fourth phase, the one involving data analysis and the definition of the Smart performance indicators, plays an essential role. This work proposes a method of Data Analysis, focusing on the fourth step of the methodology just described before.

### 1.5.1 Performance and Composite Indicators

The task of evaluating and synthesizing the various aspects of a territorial level is attributed to the indicators: already used in various scientific fields, they assess the specific performance of the case study and allow the analysis of a large amount of data. Furthermore, the indicators underline potential and weakness of an object from different perspectives. Finally, they give the possibility to create a ranking.

"An indicator is a specific, observable and measurable characteristic that can be used to show changes or progress a program is making toward achieving a specific outcome." [18].

Indicators should be created following certain characteristics, otherwise the information will lose their validity and their effectiveness. According to [18], a list of useful characteristics for developing good indicators are proposed:

- Valid and meaningful

An indicator should show the phenomenon it is intended to measure and should respond to the needs of the user.

- Sensitive

The sensitivity underlines how an indicator could vary according to the change of the measured phenomenon.

- Easily interpreted

Indicators should be sufficiently simple to be legible by users ( e.g. it should be clear what the indicator is measuring).

- Comparable

Indicators need to quantitative evaluate the project- goals, but it should also be consistent with those used in international indicators researchers in order to compare it with them.

- Disagreeable

Indicators should be able to be broken down into sub-indicators or areas of particular interest.

- Adaptable

The difficulty to gather useful information for the analysis is proof of the fact. Data are not always available from a trustful source or it's difficult to obtain from the administration's office or public institution. The planners should, therefore, adjust and adopt indicators accordingly to measure the required information in the best way possible.

Moreover, two different types of indicators could be found: individual, which measure a specific object and composite, that collects several indicators to measure a more complex concept. Individual indicators should be carefully detailed and specific for the phenomena that aim to describe.

Regarding the composite one [19], they can divide through an aggregation scheme which usually follows this line: index, sub-index (optional), indicator, variable.

After the data collection and the definition of the indicators, to obtain CIs is the normalization of the data to make them comparable. Then, they can be aggregated and weighted considering possible correlations and compensability issues among the indicators. Several normalization methods could be used, as showed in the literature [20,21]. The choice of the normalization method depends on the nature of the indicators itself and designer skills. Among the weighting and aggregation process, different approaches are presented [22]. Some of them could be grouped on the "Additive methods", in which results of all indicators are summed linearly to obtain a final weight. Normalization methods can be used if the units of some indicators are different. Another kind of approaches' are referred to as the geometric method. This type of aggregation method uses the geometric mean to obtain the final value. Finally, another method applied for this issue is the Non-compensatory Multi-criteria Analysis, that uses pairwise comparisons in order to generate a ranking with the best performing alternative.

This kind of approaches, grouped inside the Multiple - Criteria Decision Making (MCDM), will be investigated deeply in the second chapter of this work. Keeping in mind that the relationship aggregation and weighting should be analysed carefully to avoid double counting or unreliable final data.

### 1.5.2 Composite Indicators (CI) proposed

Nowadays, a lot of frameworks have been applied to university campus but only energy and environmental indicators, have been studied as in [23,24]. There is a clear lack of a global approach to the system, which could overlook all the other aspects of the campus such as social, economic issues. Starting from these considerations, in those studies, many different indicators have been combined and recovered to be able to develop a global scenario of composite indicators, Sources for the definition of the Smart indicators are [25,26].

Basing on the literature review carried out by [27], it was possible to build an aggregation scheme, following this line: index, sub-indicator, indicator, variable. Table 2 showed the different level of the Composite Indicators construction and elaboration. In the next paragraph, the entire standardization's steps will be defined in detail.

Table 2: Standardization and aggregation process of CI

| *Level 1* | *VARIABLE* |
|---|---|
| Standardization Steps | The Standardization process (z-scores method, percentage difference and so on) |
| | Qualitative weights |
| | Final weighted score |
| *Level 2* | *INDICATOR* |
| Standardization Steps | Qualitative weights |
| | Final weighted score |
| | The average score of the variables involved by the Indicators |
| *Level 3* | *SUB INDICATOR* |
| Standardization Steps | Qualitative weights |
| | Final weighted score |

| | |
|---|---|
| | The average score of the Indicators involved by the Sub indicators |
| *Level 4* | *INDEX* |
| Standardization Steps | Qualitative weights |
| | Final weighted score |
| | The average score of the Sub indicators involved by the Index |

In agreement with OECD, the handbook for developing composite indicators [22], it is necessary to standardize all CI, in order to be able to aggregate and compare them. In fact, the different nature of the data requires an operation of untying from the original units of measure.

As aforementioned in the previous paragraphs, many methods for standardization of variables are proposed in literature and even though there is not a perfect method, the choice should be oriented to the "best way" for the case study.

Keeping in mind, that those CI (Tables 3,4,5,6,7) could be adapted to the specific Campus, allowing designers to deeply specify the variables depending on the real case under analysis.

Table 3: The Living the Campus's CIs

| *Variable* | *Indicator* | *Sub-indicator* | **Index** |
|---|---|---|---|
| Average annual student number / classrooms number | Primary | Services | LIVING THE CAMPUS |
| Equivalent student ( square meter per students ) | | | |
| Equipped classroom number (chairs, blackboard, projectors et al) | | | |
| Sanitary service number / total students ratio | | | |
| Dining service presence | Secondary | | |
| Dining service capacity between 12:30 p.m. and 14.30 p.m. | | | |
| Wi-Fi covered area / total area campus | Web- online sities | | |
| Procedures that can be activated on web / total procedures | | | |
| Total annual events | Events | | |
| Total annual companies meeting | Future job | | |
| Total art and culture event | External events | | |

| | | | |
|---|---|---|---|
| Historic and artistic buildings and views (ITACA's indicators ) | Context evaluation | Context | |
| Average registered students | Inscription | Students | |
| Average registered foreign students | | | |
| Persistence badger | Badger | | |
| Bachelor graduated / total students ratio | Graduation rates | | |
| Master graduated / total students ratio | | | |
| Number of the graduates who declare that they have a paid work activity in 2015 | | | |
| Erasmus students in 2013-2014 / total students ratio in 2013-2014 | International exchanges | | |
| Erasmus scholarships needed in 2013-2014 / total scholarship ratio in 2013-2014 | | | |
| Number of foreign universities hosting Italian students for Erasmus | | | |
| Number of students / number of professors ratio | Teaching | Academy | |
| Number of engineering PhD scholarship in 2016 / number of university PhD scholarship | | | |
| Number of ordinary professors / Total professors ratio | | | |
| Number of associate professors / Total professors ratio | | | |
| Number of researchers / total professors ratio | | | |
| Total research funded by the PRIN program in the three-year period 2008-2009-2010 / average of professors | Research | | |
| Number of publications in 2015 / total professors ratio | | | |

Table 4: The Environmental CIs

| *Variable* | *Indicator* | *Sub-indicator* | ***Index*** |
|---|---|---|---|
| Not recyclable waste production / Campus users | | | **VIRONMENTA** |

| | | | |
|---|---|---|---|
| ratio | Production | Waste | |
| Paper consumption per year | | | |
| Recyclable waste production / Campus users ratio | Recyclable waste | | |
| Daily water consumption | Water consumption | Water | |
| Reused rainwater and wastewater / water consumed ratio | Sustainability | | |
| Number of classrooms with window area > 1/8 of classroom area | Indoor pollution | Air quality | |
| Number of offices with > 1/8 of office area | | | |
| Indoor air quality | | | |
| Vegetated areas / number of users | Density | Landscape | |
| Green area equipped / green area ratio | Green areas | | |
| Eating areas within 1km | Context | | |

Table 5: The Energy CIs

| *Variable* | *Indicator* | *Sub-indicator* | ***Index*** |
|---|---|---|---|
| Renewable energy produced | Sources of energy | Production and Distribution | **ENERGY** |
| Number of black out | Grid | | |
| Presence of intelligent devices | Building | Consumption | |
| Energy demand ratio / floor area with energy certificate (class E) | | | |
| Energy efficient appliances / total appliances ratio | | | |
| Number of machines control in a year | Maintenance | | |

Table 6: The Economy CIs

| *Variable* | *Indicator* | *Sub-indicator* | ***Index*** |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Incomes trend of a chosen years (3-year) | Incomes | Investments and expenses | ECONOMY |
| Expense trend of a chosen years (3-year) | Expenses | | |
| Investments in laboratories, furniture’s | funding’s for the campus innovation | Innovation | |
| Spin-off and international partnership with industries | Spin-off and partnership industries | Partnership | |

Table 7: The Mobility CIs

| *Variable* | *Indicator* | *Sub-indicator* | ***Index*** |
|---|---|---|---|
| Parking area/n of professors | Parking | Infrastructure network | MOBILITY |
| Disabled people accessibility | Accessibility | | |
| n of lifts | | | |
| n° of lifts for disabled people | | | |
| Presence of fire stairs | | | |
| n° of autobus paths within 1km | Public transport | Green mobility | |
| Car pooling | Sharing transport | | |
| Bike sharing | | | |
| Electric students bus | | | |
| Car sharing | | | |

### 1.5.3 Standardization, aggregation and weighting of the CI

All data could not be synthesized by the same method, but two or three methods have been identified for the standardization of the variables, based on their nature and way of comparison. For our case study, the used methods are the method Z-Scores and the percentage difference. The first one is useful for comparing data coming from other sources: in this case the comparison is focused on a big amount of data taken from of the different university of Italy, with the same size and number of faculties. The second one was chosen in order to standardize all variables based on an optimal target (for example imposed by law).

The Z-Scores method transforms data through mean ($M_x$) and standard deviation ($S_x$), allowing to derive the final value Z. Therefore, it is possible to convert the individual variable to a common scale with a mean M=100 and a standard deviation S=10: the obtained values will range approximately in the interval (70-130). Let X = {$X_{ij}$} be the matrix of n rows (university campuses) and m columns (variables), let $M_{xj}$ and $S_{xj}$ denote the mean and the standard deviation of the j-th variable (Equation 1, 2):

$$M_{xj} = \frac{\sum_{i=1}^{n} x_{ij}}{n}$$

Equation 1.

$$S_{xj} = \sqrt{\frac{\sum_{i=n}^{n} \left(x_{ij} - M_{xj}\right)^2}{n}}$$

Equation 2.

The standardized matrix Z = {$Z_{ij}$} is (Equation 3):

$$z_{ij} = \frac{\left(x_{ij} - M_{xj}\right)}{S_{xj}} \cdot 10 + 100$$

Equation 3.

The percentage difference was very useful to standardize all those variables that had to express their performance in relation to an existing optimum target. Given the initial value $x_i$ to standardize and $x_f$ the value to be achieved, the applied equation is as follows (Equation 4):

$$\Delta\% = \left(\frac{x_f - x_i}{x_f}\right) \cdot 100$$

Equation 4.

In this way, it was possible to transform the initial data into numerical values: the values taken from the Z-Scores are contained in the scale from 70 to 130; those derived from the percentage difference, however, are distributed in a range of 0% to 100%.

Since multiple methods of standardization of the data have been used, an aggregation method is also required in order to bring back the different values into a unique range. It was necessary to choose an arbitrarily score range, from -3 to + 3, thus bringing the scale of the values Z-Scores (70 to 130) and the scale of the percentage difference (from 0% to 100%) into this range, as shown in Figure 2.

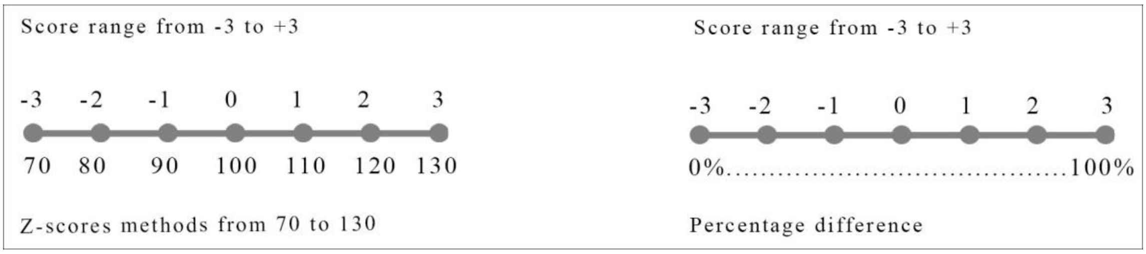


Figure 2: Aggregation method.

After that, it is possible to transform all the variables in their respective indicators, following the aggregation scheme already described in Table 2.

The final step involves the weighting process: a weight to each element (variable, sub-indicator and indicator) have been assigned, to determine the importance of each of them in the composition of the final Index. The criterion adopted is a subjective criterion based on a percentage weight assigned by the authors. This method is the Additive Averaging [28]. An example is shown in Figure 3.

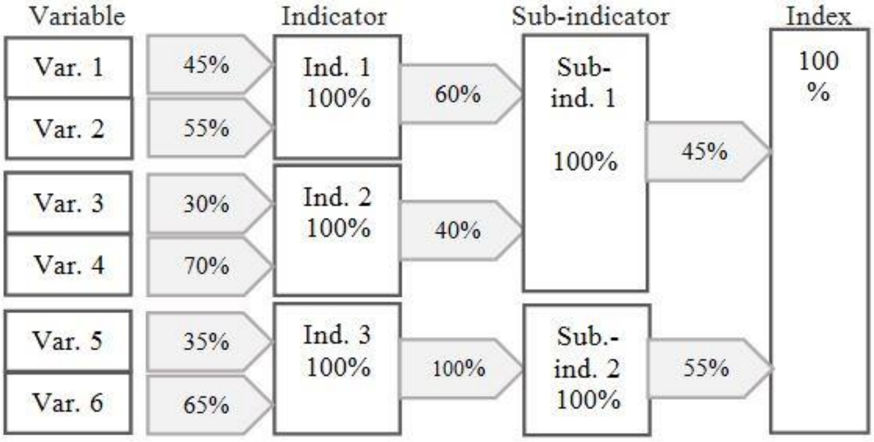


Figure 3: Example of the weighting process

## 1.6 Case study: Faculty of Civil and Industrial Engineering, Sapienza, University of Rome

The case study is the Civil and Industrial Engineering faculty of La Sapienza University of Rome. The historic building which hosts this University was built in 440 B.C. At the end of the 15th, century Francesco Della Rovere started to restore the basilica adding to it another building, used for conventual communities. Only since the 19th century, it began to be used as a school, namely as a Math and Drawing Superior School. The building was therefore subjected to some extensions and adjustments. In the end, in the first years of the 20th century, due to the overcrowding space for the increasing number of students, many other structures were built next to the original building. Nowadays, the academic complex consists of eight different buildings containing classrooms, libraries, offices (Figure 4). The singularity of this academic campus is due to the historical nature of the buildings, in particular the famous indoor cloister, which became the symbol of this university.

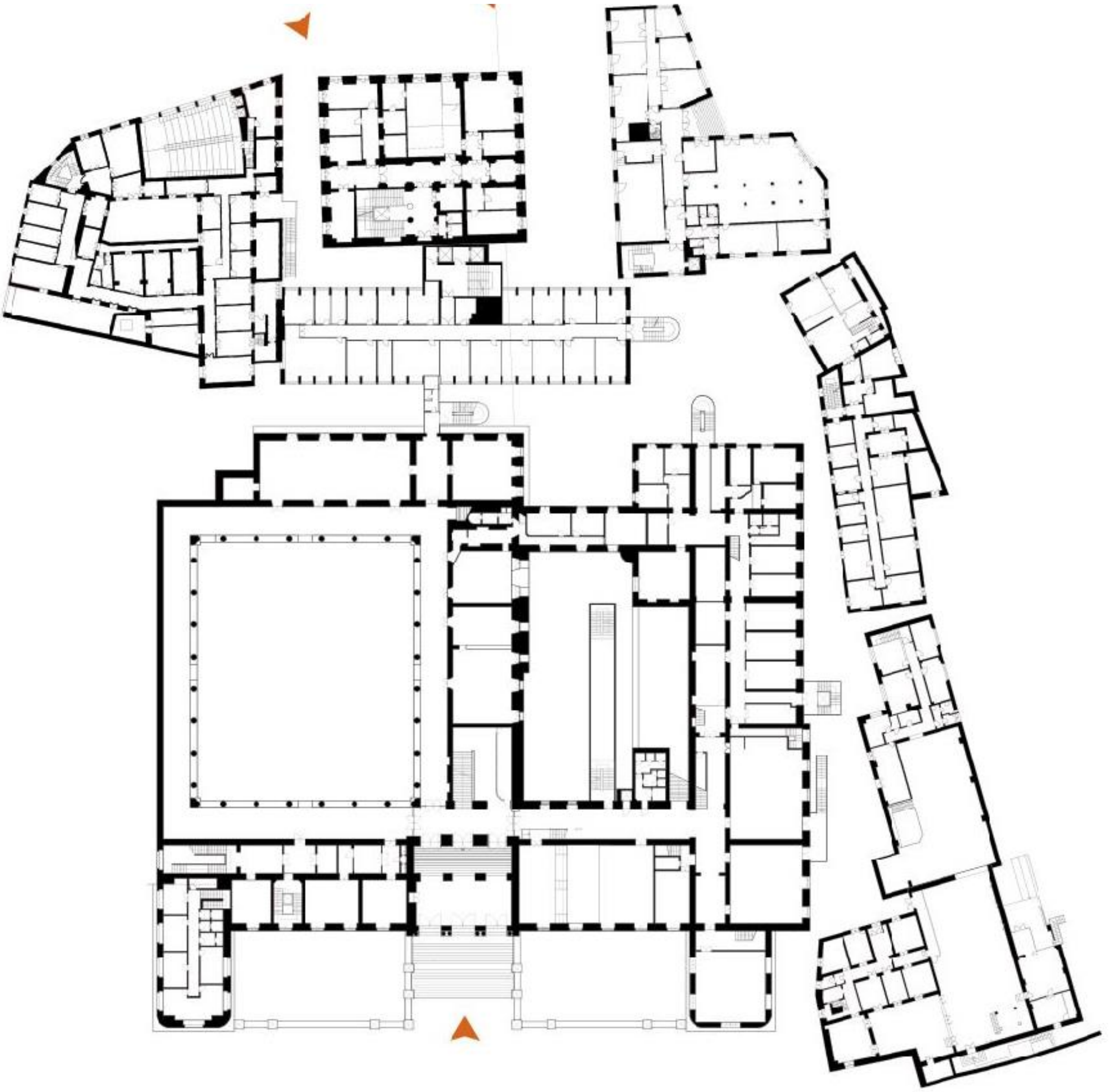


Figure 4: Ground floor plan of the campus

## 1.6.1 Methodology application

According to the methodology described in the previous paragraphs, the first steps are the preliminary planning that involves the analysis of the characteristics of the urban context.

The San Pietro in Vincoli campus is a multifunctional complex, characterized by an exceptional history, as it was explained previously. The most important data of this campus, therefore, is related to its historical, structural, operational, demographic and academic characteristics. Data were provided by different sources: university offices, online web-site, Sapienza administrative offices, especially for the economic and energy information. The phase of the data collection was not easy and it takes time to obtain official permissions to manage some information. This issue is nowadays very common and the designers have to face with it.

The definition of the smart axis was done, following the IMM methodology. Five smart fields, therefore, are chosen: Energy, Economy, Environment, Mobility, Living the campus.

The standardization process was developed for all the CIs, following the process described previously. Then, it was possible to elaborate the final score for each smart field, understand the strength and weakness of the Campus, before any smart solution implementation. Rankings of the current state of the Campus was therefore draft. Finally, several strategies were proposed to overcome the limits and problems of the campus.

The Incidence Matrix were elaborated for the smart axis, analysing the impact of the presented solutions on each filed. In the next paragraphs, the author will show the results about the smart ranking and of the winner strategies, that obtained the maximum score inside the matrix.

## 1.7 Results and discussion

### 1.7.1 Composite Indicators results

This analysis has been developed for all the smart fields. Due to the easiness of the readers, only the Living the campus's results were divided into two parts to show the entire calculation's process of each variable (Table 8, I-II). The other tables (Table 9,10,11,12) start from the indicator's standardization, keeping in mind that the variables of each smart field (showed in Table 4,5,6,7) were analyzed. The average of the indicators is, therefore, the results of the respective variables calculation. Some considerations about the scores obtained by indicators will be done below each table.

Table 8: Living the Campus results (I)

| *Variable* | X initial | X final | Δ% | score | weight | weighted value | *Indicator* |
|---|---|---|---|---|---|---|---|
| Average annual student number / classrooms number | 23.24 | 50.00 | 53.51 | 2.00 | 0.10 | 0.20 | Primary |
| Equivalent student (square meter per students ) | 1.80 | 4.00 | 55.00 | -0.30 | 0.40 | -0.12 | |
| | 1.80 | 4.00 | 55.00 | -0.30 | 0.40 | -0.12 | |
| Equipped classroom number (chairs, blackboard, projectors et al) | 35.00 | 40.00 | 12.50 | 2.25 | 0.20 | 0.45 | |
| Sanitary service number/total students ratio | 17.00 | 30.00 | 43.33 | 0.40 | 0.30 | 0.12 | |
| Dining service presence | 1200.00 | 2122.00 | 43.45 | 0.39 | 0.50 | 0.20 | Secondary |
| Dining service capacity between 12:30 p.m. and 14.30 p.m. | yes | yes | Yes | 3.00 | 0.50 | 1.50 | |
| Wi-Fi covered area / total area campus | 0.88 | 1.00 | 12.00 | 2.28 | 0.60 | 1.37 | Web- online |
| Procedures that can be activated on web / total procedures | 80.00 | 100.00 | 20.00 | 1.80 | 0.40 | 0.72 | |
| Total annual events | 123.00 | 335.00 | 63.28 | -0.80 | 1.00 | -0.80 | Events |
| Total annual companies meeting | 52.00 | 335.00 | 84.48 | -2.07 | 1.00 | -2.07 | Future job |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Total art and culture event | 60.00 | 80.00 | 25.00 | 1.50 | 1.00 | 1.50 | External events |
| Historic and artistic buildings and views (ITACA's indicators ) | 100.00 | 100.00 | 1.00 | 3.00 | 1.00 | 3.00 | Context evaluation |
| Average registered students | z-scores method | | | 0.50 | 0.60 | 0.30 | Inscription |
| Average registered foreign students | z-scores method | | | 1.00 | 0.40 | 0.40 | |
| Persistence badger | z-scores method | | | 0.60 | 1.00 | 0.60 | Badger |
| Bachelor graduated / total students ratio | z-scores method | | | 1.40 | 0.35 | 0.49 | Graduation rates |
| Master graduated / total students ratio | z-scores method | | | 1.80 | 0.35 | 0.63 | |
| n° of the graduates who declare that they have a paid work activity in 2015 | z-scores method | | | -0.50 | 0.30 | -0.15 | |
| Erasmus students in 2013-2014 / total students ratio in 2013-2014 | z-scores method | | | 2.30 | 0.50 | 1.15 | International exchanges |
| Erasmus scholarships needed in 2013-2014 / total scholarship ratio in 2013-2014 | z-scores method | | | 2.30 | 0.30 | 0.69 | |
| n° of foreign universities hosting Italian students for Erasmus | z-scores method | | | -2.50 | 0.20 | -0.50 | |
| n° of students / n° of professors ratio | z-scores method | | | 2.40 | 0.10 | 0.24 | Teaching |
| n° of engineering PhD scholarship in 2016 / n° of university PhD scholarship | z-scores method | | | -0.80 | 0.30 | -0.24 | |
| n° of ordinary | z-scores method | | | 2.40 | 0.20 | 0.48 | |

| | | | | | |
|---|---|---|---|---|---|
| professors / Total professors ratio | | | | | |
| n° of associate professors / Total professors ratio | z-scores method | 1.20 | 0.20 | 0.24 | |
| n° of researchers / total professors ratio | z-scores method | -1.30 | 0.20 | -0.26 | |
| Total research funded by the PRIN program in the three-year period 2008-2009-2010 / average of professors | z-scores method | -2.50 | 0.60 | -1.50 | Research |
| n° of publications in 2015 / total professors ratio | z-scores method | 2.30 | 0.40 | 0.92 | |

Table 8: Living the Campus results (II)

| *Indicator* | average | weight | weighted value | *Sub-indicator* | average | weight | weighted value | **Index** | Score |
|---|---|---|---|---|---|---|---|---|---|
| Primary | 0.650 | 0.350 | 0.228 | Services | 0.74 | 0.40 | 0.30 | **LIVING THE CAMPUS** | 0.80 |
| Secondary | 1.697 | 0.200 | 0.339 | | | | | | |
| Web-online | 2.088 | 0.150 | 0.313 | | | | | | |
| Events | -0.8 | 0.1 | -0.08 | | | | | | |
| Future job | -2.1 | 0.1 | -0.21 | | | | | | |
| External events | 1.5 | 0.1 | 0.15 | | | | | | |
| Context evaluation | 3.00 | 1.00 | 3.00 | Context | 3.00 | 0.10 | 0.30 | | |
| Inscriptio | 0.70 | 0.20 | 0.24 | Students | 0.96 | 0.20 | 0.19 | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| n | | | | | | | | | |
| Badger | 0.60 | 0.35 | 0.21 | | | | | | |
| Graduation rates | 0.97 | 0.25 | 0.24 | | | | | | |
| International exchanges | 1.34 | 0.20 | 0.27 | | | | | | |
| Teaching | 0.46 | 0.60 | 0.28 | Academy | 0.04 | 0.30 | 0.01 | | |
| Research | -0.58 | 0.40 | -0.23 | | | | | | |

The maximum score was achieved by the context evaluation indicator, due to the historical characteristics of the urban area, such as the presence of the Colosseum. Then, secondary service obtained a good evaluation, since the campus is well organized for the dining services. Conversely, the primary service seems to be not enough for satisfying the student's needs, due to the spaces limitations. Finally, the indicator that achieved the lower score is the Research one, since the campus is not able to guarantee tools and services for this field.

Table 9: Environmental results

| *Indicator* | average | weight | weighted value | *Sub-indicator* | average | weight | weighted value | **Index** | average |
|---|---|---|---|---|---|---|---|---|---|
| Production | 1.14 | 0.50 | 0.57 | Waste | -0.18 | 0.40 | -0.07 | **ENVIROMENTAL** | 0.65 |
| Recyclable waste | -1.49 | 0.50 | -0.75 | | | | | | |
| Water consumption | 3.00 | 0.80 | 2.40 | Water | 1.80 | 0.20 | 0.36 | | |
| Sustainability | -3.00 | 0.20 | -0.60 | | | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Indoor pollution | 1.60 | 1.00 | 1.60 | Air quality | 1.60 | 0.30 | 0.48 | | |
| Green area | -1.20 | 1.00 | -1.20 | Landscape | -1.20 | 0.10 | -0.12 | | |

Regarding the environmental indicators, the worst score is obtained by the sustainability indicator, that it takes into account the percentage reuse of wastewater. The campus is not equipped with a recycling water system, therefore the indicator shows this negative value. Among the sustainability aspect, the Recyclable waste indicator obtained a negative value too, since the recycling is not adopted for all the building inside the complex.

Table 10: Energy results

| *Indicator* | Av. | Weight | weighted value | *Sub-indicator* | average | weight | weighted value | ***Index*** | average |
|---|---|---|---|---|---|---|---|---|---|
| Sources of energy | -3.00 | 0.70 | -2.10 | Production and Distribution | -1.80 | 0.60 | -1.08 | **ENERGY** | -1.36 |
| Grid | 1.00 | 0.30 | 0.30 | | | | | | |
| Building | -1.60 | 0.65 | -1.04 | Consumption | -0.69 | 0.40 | -0.28 | | |
| Maintenance | 1.00 | 0.35 | 0.35 | | | | | | |

As showed in the table above, the energy smart axis obtained the worst score, due to the old envelope of the building and to the presence of obsolete technical system plant. In detail, the source of energy indicator achieved a point of minus three since it represents the relationship between the use of renewable sources respect to the energy needs. As aforementioned, the campus uses the only traditional source of energy such as gas for the thermal systems. Following, the building indicator highlights the lower envelope performances of the entire complex, that still need a consistent energy requalification.

Table 11: Economy results

| *Indicator* | average | weight | weighted value | *Sub-indicator* | average | weight | weighted value | **Index** | average |
|---|---|---|---|---|---|---|---|---|---|
| Incomes | 3.00 | 0.65 | 1.95 | Investments and expenses | 3.00 | 0.45 | 1.35 | **ECONOMY** | 0.71 |
| Expenses | 3.00 | 0.35 | 1.05 | | | | | | |
| funding's for the campus innovation | -1.60 | 1.00 | -1.60 | Innovation | -1.60 | 0.35 | -0.56 | | |
| Spin-off and partnership industries | -0.40 | 1.00 | -0.40 | Partnership | -0.40 | 0.20 | -0.08 | | |

Among the economy field, indicators related to the spin-off and the implementation of innovative solutions registered low scores compared to the other ones. Those results underline the importance of future job investment for graduated students.

Table 12: Mobility results

| *Indicator* | average | weight | weighted value | *Sub-indicator* | average | weight | weighted value | **Index** | average |
|---|---|---|---|---|---|---|---|---|---|
| Parking | -0.90 | 1.00 | -0.90 | Infrastructure network | 1.00 | 0.70 | 0.70 | **MOBILITY** | 0.61 |
| Accessibility | 0.90 | 0.40 | 0.36 | | | | | | |
| Public transport | 1.50 | 0.60 | 0.90 | Green mobility | -0.30 | 0.30 | -0.09 | | |
| Sharing transport | -0.75 | 0.40 | -0.30 | | | | | | |

Finally, the table above showed the situation related to the mobility of the Campus. Parking and Sharing transport indicators obtained negative value since only the car-sharing is the service active for the campus's users. Moreover, the presence of a few parking dedicated to the campus is available near the university. Accessibility indicator is positive but reached a low score since not all the buildings present elevator for disabled people. On the other hand, the public transport one showed the best score, due to the presence of the metropolitan services combined with the bus one.

Then, it is possible to draft the final ranking of the stat of art of the Campus, in order to identify the smart axis that presents several problems (Table 13).

Table 13: Smart Ranking results

| Ranking | Smart axis | Scores |
|---|---|---|
| **1** | Living the Campus | 0.80 |
| **2** | Economy | 0.71 |
| **3** | Mobility | 0.61 |
| **4** | Environment | 0.65 |
| **5** | Energy | -1.36 |

Living the campus has achieved the highest score: the sub-indicators, such as academia and students, demonstrate the good quality of teaching and services. On the other hands, the Energy field got the worst score, especially the sub-indicator "Source of energy", showing the lack of renewable energy systems within the building. Those energy negative results are reasonable due to the old age of the campus. Finally, the environment field, which has an average score, highlights the weak management of the recyclable waste service. Basing on that weakness, the strategies can be planned to give accurate and smart solutions, solving the current problems of the campus.

### 1.7.2 The Qualitative Incidence Matrix development

After the problems categorizations, the following step is to propose a set of strategies for each smart axis able to solve the weakness of the campus. Designers could define different solutions, without any limits regarding the number of them. However, the role of the planners is to evaluate in detail a few of them, knowing their potentialities.

Fort this case study, only the economic field was not taken into account since it is a complex aspect that involved so many actors that it will be difficult to quantify in this work. Tables 14,15,16,17 collect therefore the impact of those solutions for all the smart axes.

Table 14: Living the Campus incidence matrix

| **AXIS** | **LIVING THE CAMPUS** | | | |
|---|---|---|---|---|
| | **Strategies** | | | |
| | Furniture for the Cloister | Redevelopment of abounded space | Interactive systems | Services |
| | **Actions** | | | |
| | **Furniture** | **Smart Square** | **Display** | **Sanitary services** |
| EN | None | Energy saving thanks to the light dimming and smart systems | Energy consumed | None |
| | 0 | [+1] | [-1] | 0 |
| ENV | Use of recycling materials | $CO_2$ reduction | None | None |
| | [+1] | [+1] | 0 | 0 |
| EC | Economy saving | High initial investment partially covered by sponsors | Low investment | Medium investment |
| | [+1] | [+1-1] | [-1] | [+1] |
| MOB | None | None | Increase mobility | None |
| | 0 | 0 | [+2] | 0 |
| LIV | Increase of comfort indoor | Smart and technological space | Increase of comfort indoor | Increase of primary service |
| | [+1] | [+3] | [+1] | [+3] |
| Score | 3 | 6 | 1 | 4 |
| SS | 0.2 | 0.3 | 0.1 | 0.4 |
| FS | 0.3 | 0.15 | 0.25 | 0.3 |
| TS | 0.4 | 0.1 | 0.3 | 0.2 |
| TOT | 3.9 | 6.55 | 1.65 | 4.9 |

Actions proposed for this smart axis are: the installation of the furniture inside green and collective spaces, the implementation of a Smart Square, the installation of information display at the entrance and exit of the campus, the increased of sanitary services. The winner action is the implementation of a

Smart Square that includes many services such as smart benches, a new space for dining and so on.

Table 15: Environment incidence matrix

| **AXIS** | **ENVIRONMENT** | | | |
|---|---|---|---|---|
| | **Strategies** | | | |
| | Waste | | | Air Quality |
| | **Actions** | | | |
| | **Use of Compactors** | **Game app (waste's dictionary)** | **Use of Eco Box** | **Environmental sensors** |
| EN | Gas fuel saving partially covered by renewable source (PV panels) | None | None | Energy consumed by sensors |
| | [+1-1] | 0 | 0 | [-1] |
| ENV | No full garbage bin thanks to wireless signals | Sustainability advantages | Printer cartridges recycling | Dangerous parameters controls |
| | [+1] | [+2] | [+1] | [+2] |
| EC | Installation cost [-1] | Reduction of non-recycling waste management cost [+1] | Economic saving [+1] | Installation cost [-1] |
| | | | | |
| MOB | Reduction of km for waste lorry | None | Mobility for printer cartridges exhausted collection | None |
| | [+1] | 0 | [-1] | 0 |
| LIV | Increase of environmental quality | Student’s awareness for sustainability field | Increase of environmental quality | Real time data; increase of environmental quality |
| | [+2] | [+1] | [+1] | [+2] |
| Score | 4 | 4 | 2 | 2 |
| SS | 0.3 | 0.2 | 0.15 | 0.35 |
| FS | 0.3 | 0.3 | 0.25 | 0.15 |
| TS | 0.25 | 0.45 | 0.2 | 0.1 |
| TOT | 4.85 | 4.95 | 2.6 | 2.6 |

The use of compactors, the Game App, the use of Eco box and the environmental sensors are the actions exposed to facing problems related to the environmental field. The Game App ones win the rankings, followed by the action of use of compactors. The aims of the winner solution are involved students in the process of sustainability in order to increase the environment's care.

Table 16: Energy incidence matrix

| **AXIS** | **ENERGY** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Strategies** | | | | | | | |
| | Lighting | | Monitoring | Efficiency of the envelope | | | Efficiency of energy plant | |
| | **Actions** | | | | | | | |
| | **Light sensor** | **LED re-lamping** | **Monitoring system** | **New window fixtures** | **New shading** | **New plaster** | **Radiator installation** | **Condensation Boiler** |
| EN | Energy saving | | | | | | | |
| | [+1] | [+1] | [+1] | [+1] | [+1] | [+1] | [+1] | [+1] |
| ENV | $CO_2$ reduction | | | | | | | |
| | [+1] | [+1] | [+1] | [+1] | [+1] | [+1] | [+1] | [+1] |
| EC | Investment partially balanced by the economy saving of the bills | | | Investment balanced by the national incetives | | | | |
| | [+1-1] | [+1-1] | [-1+1] | [+1] | [+1] | [+1] | [+1] | [+1] |
| MOB | None | Advantages for the indoor mobility | None | None | None | None | None | None |
| | 0 | [+1] | 0 | 0 | 0 | 0 | 0 | 0 |
| LIV | Increase of visual comfort | No dangerous gas emission; possibility of psicological effects | Control of the energy demand | Increase of visual and thermal indoor comfort | | | | |
| | [+1] | [+1-1] | [+1] | [+1] | [+1] | [+1] | [+1] | [+1] |
| Scor | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| e | | | | | | | | |
| SS | | 0.2 | 0.2 | 0.15 | 0.15 | 0.00 | 0.15 | 0.15 |
| FS | | 0.2 | 0.1 | 0.25 | 0.25 | 0.00 | 0.15 | 0.05 |
| TS | | 0.3 | 0.15 | 0.15 | 0.15 | 0.15 | 0.05 | 0.05 |
| TOT | 3 | 3.7 | 3.45 | 4.55 | 4.55 | 4.15 | 4.35 | 4.25 |

As being the worst axis, several solutions have been proposed for the energy sector. The lighting, the technical system monitoring, the efficiency of the building envelope and the energy plants are the macro area investigated. Results of the matrix highlight the efficiency of the envelope obtained the high score. This action is divide into two: the implementation of new window fixtures and the application of shading systems. This action is followed by the efficiency of the energy plant due to the presence of obsolete technical ones. Moreover, the differences between them in terms of the score depends on the additional weights (SS, FS and TS).

Table 17: Mobility incidence matrix

| AXIS | **MOBILITY** | | | |
|---|---|---|---|---|
| | **Strategies** | | | |
| | Parking | Electric charging stations | Sustainable mobility | |
| | **Actions** | | | |
| | **Parking sensors** | **Electric charging stations** | **Electric bus for the campus** | **Bike sharing** |
| EN | None | Possibility of powering the system with PV panels | Consumption reduction | Consumption reduction |
| | 0 | [+1-1] | [+1] | [+1] |
| ENV | Possible reduction of pollution if powered with renewable energy; decrease of acoustic pollution | Possible reduction of pollution if powered with renewable energy; decrease of acoustic pollution | Possible reduction of pollution if powered with renewable energy; decrease of acoustic pollution | Possible reduction of pollution if powered with renewable energy; decrease of acoustic pollution |
| | [+1] | [+1] | [+1] | [+1] |
| EC | Installation cost | Installation cost | Installation cost | Installation |

| | | | | |
|---|---|---|---|---|
| | | | balanced by student taxes | cost |
| | [-1] | [-1] | [+2-1] | [-1] |
| MOB | Parking time reduction | None | Green mobility and time reduction | Green mobility and time reduction |
| | [+1] | 0 | [+2] | [+1] |
| LIV | Stress reduction | Increase of environmental quality and money savings | Comfort increase and mobility optimization, stress reduction | Stress reduction, increase of environmental quality, credits and benefits |
| | [+1] | [+2] | [+1] | [+2] |
| Score | 2 | 2 | 6 | 4 |
| SS | 0.3 | 0.15 | 0.25 | 0.3 |
| FS | 0.25 | 0.25 | 0.25 | 0.25 |
| TS | 0.2 | 0.2 | 0.35 | 0.25 |
| TOT | 2.75 | 2.6 | 6.85 | 4.8 |

Among this last smart aspect, the parking sensors, Electric charging stations and the sustainability mobility (electric bus plus bike sharing) were therefore defined. The winner action is the actualization of an electric bus service for the students able to connect the other campus’s branches.

### 1.7.3 Simulation of the Energy winner strategy

All the winner strategy could be simulated in order to quantify their feasibility and strengths. In this case, only the energy one will be simulated. An open source software called Grasshopper/Archism, was chosen for this scope. Although most energy simulation tools, such as TRNSYS and EnergyPlus, are validated by the IEABESTEST (International Energy Agency Building Energy Simulation Test and Diagnostic Method) procedures [29], but frequently reliable results are not provided for the last version of these software [30]. On the other side, open sources software are easily implemented by the users and several online platform for helping them are available [31].

Archsim Energy Modeling is a plug-in for the parametric design environment Grasshopper for Rhinoceros [32]. The thermal model class library contains abstract definitions for zones, faces, materials and can translate those into a simulation engine specific syntax [33]. Recently, it becomes a part of the DIVA environmental performance analysis suite [34]. Below the description of those tools:

- Grasshopper is a graphical algorithm interface, free plug in for Rhinoceros. This tool uses a nodes diagram to describe mathematics and geometrical relationships.
- Rhinoceros 3D is a CAD modelling software for architectural and design fields, that works with NURBS (Non-uniform Rational B-Splines). This program allows to support a large amount of environmental and energy free plug-in.
- EnergyPlus is the Grasshopper/Archsim energy engine for the analysis and thermal load simulation, elaborated by the U.S. Department of Energy’s (DOE) Building Technologies Office (BTO) and managed by the National Renewable Energy Laboratory [35].

Knowing that, the case study complex is composed of eight buildings and one of them is chosen for the energy simulation, as an example. This building host the department of Civil and Environment Engineering, few classrooms, offices and a library. It is composed of five floors with an average height of 3 m. Figure 5 shows the fourth floor and the offices highlighted in grey was chosen for the daylighting simulations, being located in the south exposition.

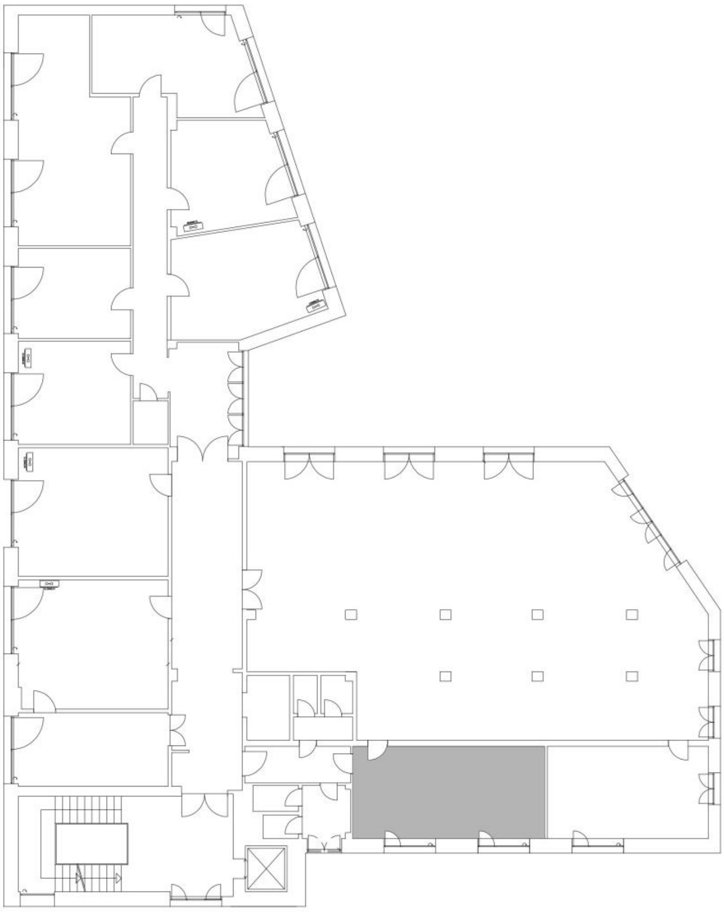


Figure 5: Plant of the office chosen

The model of the building is composed of 45 thermal zones. A thermal zone is a space or a collection of spaces having similar space-conditioning requirements and the same heating and cooling set-point. The 3D model, generated with Rhinoceros, was imported in Grasshopper as input for the "Thermal zone setting" in order to transform the geometrical model into an energy model. The thermal zone needs a specific element called "Brep" (Boundary REPresentation), useful for connecting geometrical zones together. Due to the complexity of the building composition, different components, such as Entewine, Intersector and Bang, are required in order to combine thermal zones (Figure 6).

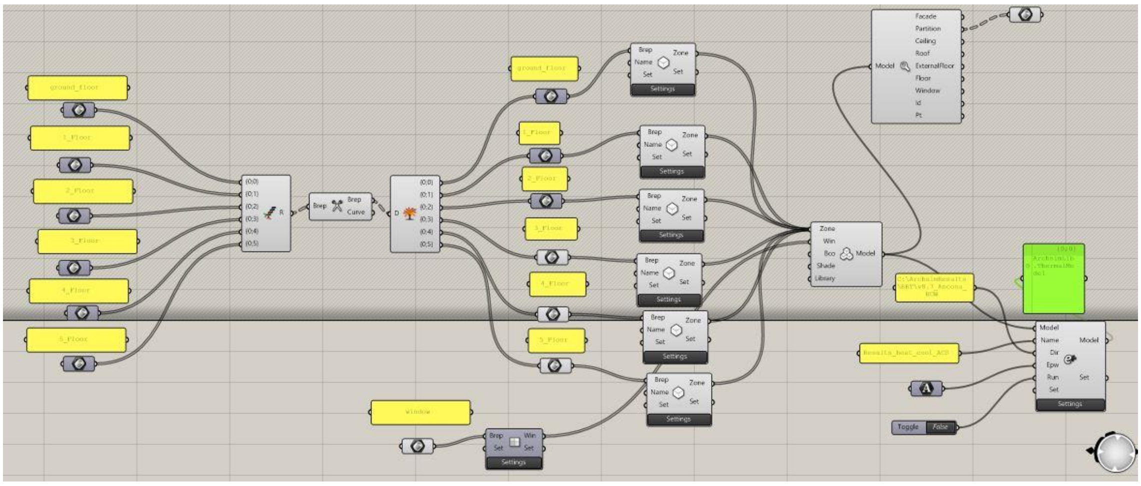
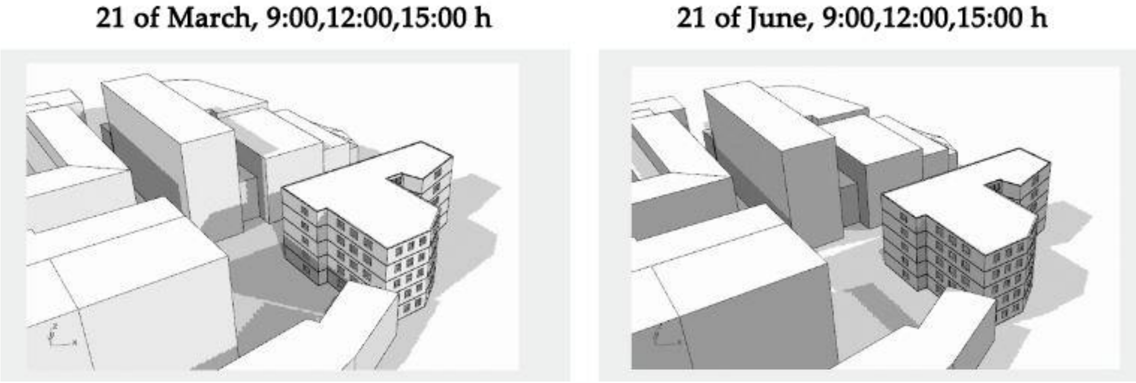


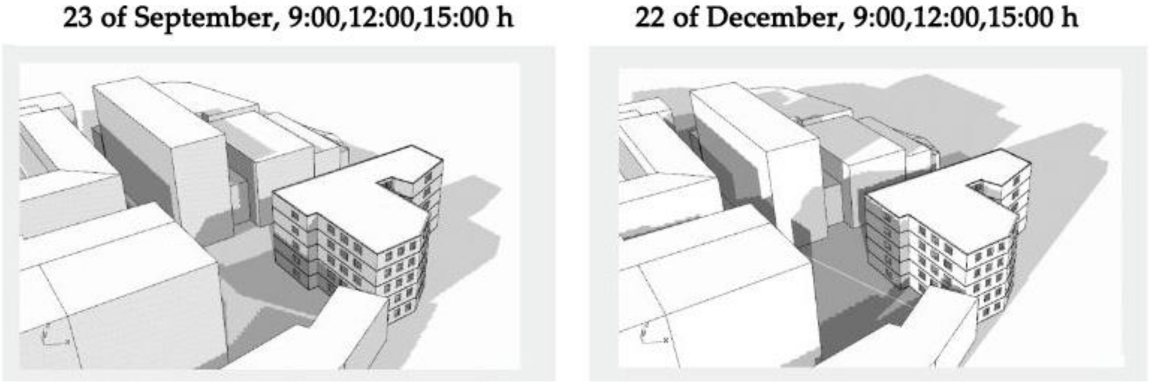
Figure 6: Archsim components

Finally, climatization inputs are the following: set-point temperature (19 °C for heating and 26 °C for cooling) and base office operative time schedules of the heating and cooling systems. Energy simulations are carried on trough ideal technical systems due to the few energy conditioning characterizations.
As aforementioned, the smart winner strategies are both the new window fixtures and the shading placement. Single glazed windows are placed in the facades of the building with a transmittance of 3.7 W/(m$^2$K). Therefore, the installation of wood and aluminium double glazed window decreases consistently the transmittance value, 2.2 W/(m$^2$K). Regarding the other solution, horizontal shadings are proposed able to guarantee the lighting and thermal indoor comfort.

A sun path simulation was done to see the shading of the entire complex on building D, as showed in Figure 7.


**21 of March, 9:00,12:00,15:00 h**

**21 of June, 9:00,12:00,15:00 h**


23 of September, 9:00,12:00,15:00 h

22 of December, 9:00,12:00,15:00 h

Figure 7: Sun path simulation of the building

Thermal analysis of the chosen office were done for the base scenario, characterized by the single glazed window and without shading. Then the other two combinations were collected: the first one taking into account only the window replacement, the other one is the combination of the two smart solutions (new window plus shading). The Operative Temperature (OT) is chosen as the final output, able to show the difference between the solutions. Below are reported the results of the simulations carried out during four months: March, June, September, December (Figures 8,9,10,11).

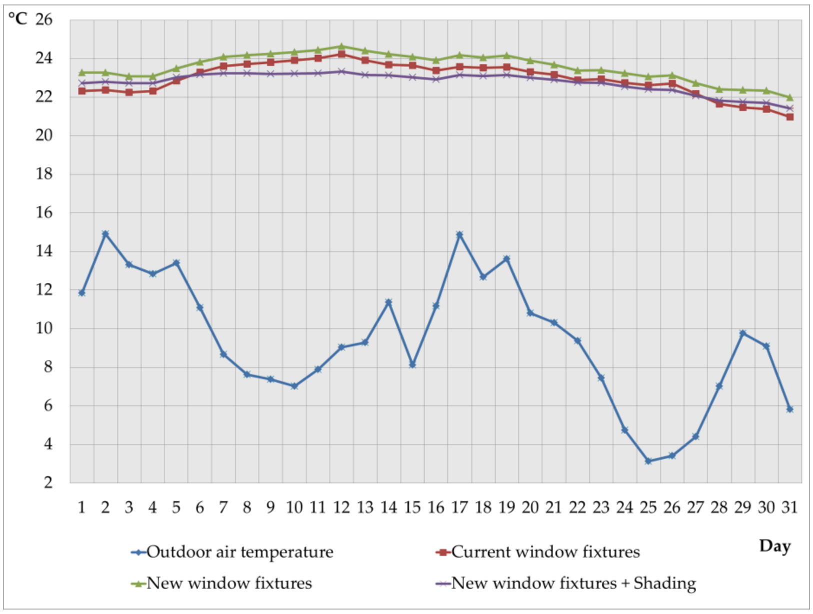


Figure 8: Thermal results of March

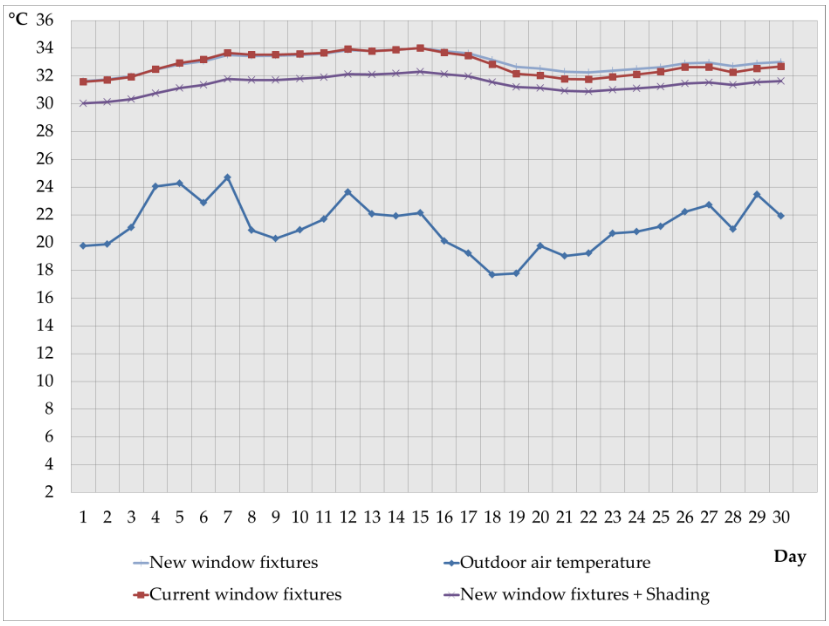


Figure 9: Thermal results of June

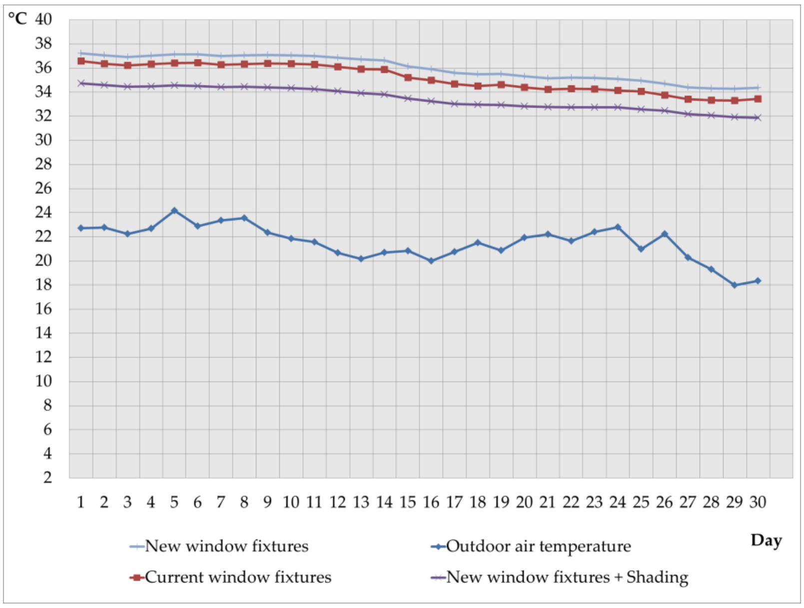


Figure 10: Thermal results of September

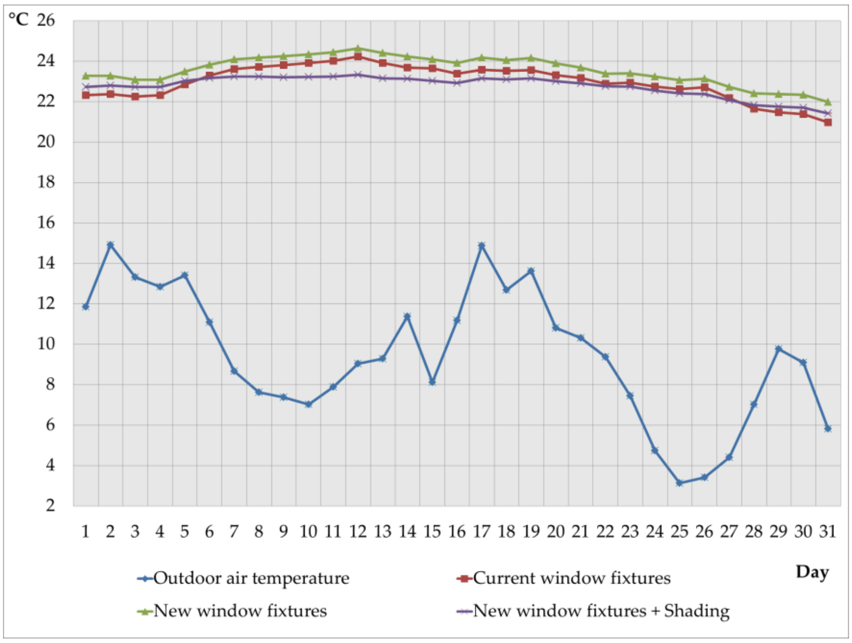
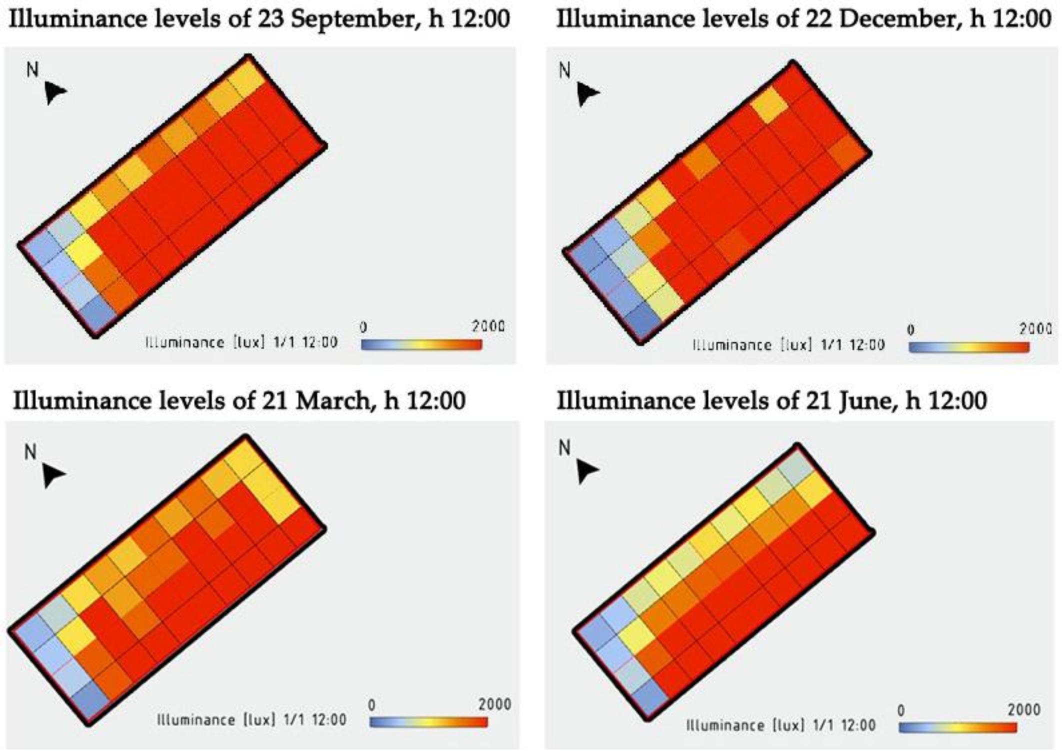


Figure 11: Thermal results of December

In general, the first combination with window fixture's more performance causes the increasing of the OT (about 1 °C), due to the low transmittance value of the new window. This issue is positive for the winter period (Figures 8,10), but for the summer one could be not suitable, especially during hot days (Figures 9,11). The shading placement is therefore essential for avoiding this problem and at the same time guaranteeing the indoor comfort. Moreover, the shading system allows to differentiate the thermal effects, maintaining the OT of the winter season aligned with the base scenario, but on the other hand allowing a sensible decrease of the OT during the hot season.

Finally, daylighting simulations were carried out to see the impact of the new shading. In line with this, illuminance levels in the base scenario (without the shading systems) are very high. An influence factor is the geometry of the space, where the relationship between the glass surface percentage and the width of the room is consistently high.


Illuminance levels of 23 September, h 12:00

Illuminance levels of 22 December, h 12:00

Illuminance levels of 21 March, h 12:00

Illuminance levels of 21 June, h 12:00

Figure 12: Illuminance levels before the interventions

It can be noticed that illimuminace values located near the window façade are quite similar in all the seasons; on the other hand, differences could be found in terms of daily lighting penetration inside the room. As showed in Figure 12, high illuminance levels are distributed in the total area of the room in December, since the sunbeams present a lower incline. An intermediate situation could be noticed during two months of March and September, where it is registered a similar illuminance level pattern inside the room. Finally, lower levels of illuminance are registered in June, since sunbeams are characterized by a consistent incline comparing to the other months.

In line with this, the horizontal shading system placement allows to decrease the illuminance values inside the room and to control lighting discomfort phenomena (e.g. dazzle). In general, results more efficient in term of illuminance levels reduction are registered in December, March and September (Figure 13).

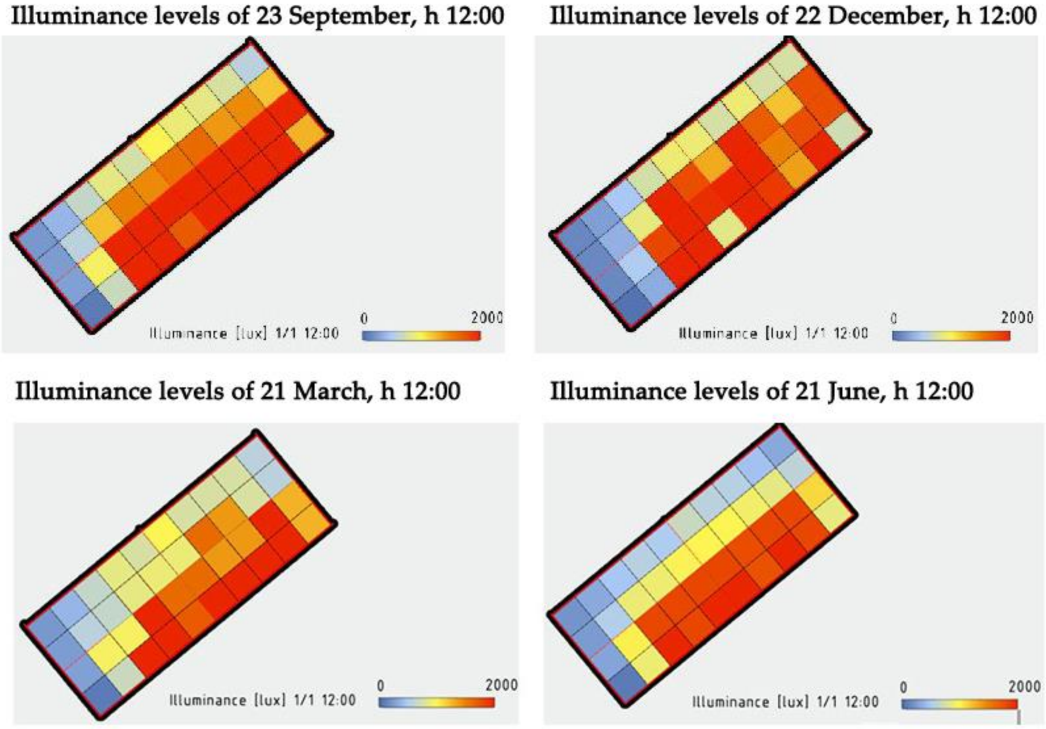


Figure 13: Illuminance levels after the interventions

Moreover, this reduction is obtained near the window façade, where illuminance levels are lower than 2000 lumen, as showed in Figure 13.

## 1.8 Conclusions

This work aims to integrate a smart methodology, the IMM approach, providing a set of Composite Indicators (CIs) for assessing a global evaluation of the academic campuses. As exposed in this chapter, the university campus could be considered as a microcosm inside a macrocosm, as a small city in a metropolis. Therefore it is possible to adapt the concept of the Smart City to a Campus.

The definition of global performance indicators and their standardizations is the most relevance steps of IMM methodology, developed by the authors in previous researches. Then, those CIs indicators and methods for data standardization and aggregation have been applied to the engineering faculty of La Sapienza University, San Pietro in Vincoli (Rome) as a case study.

The smart ranking is finally drafted, highlighted the urgent call of the complex to be refurbishment in term of energy aspects. This result is in line with the old history of the complex and its envelope's and energy plant's characteristics. Conversely, the smart axes Living the Campus obtained the best score, pointing out the variety and efficiency of the academic services.The Smart solutions were proposed for all the smart axes and they were analyzed through the Qualitative Incidence Matrix. As aforementioned, this matrix allows designers to show the positive or negative impact of those strategies, in a holistic and global framework.

The worst smart axis, the energy one, was deeply investigated, simulating the winner smart solutions to concretely provide the expected benefits. In details, those strategies are both the new window fixtures and the shading placement. The installation of wood and aluminium double glazed window decreased consistently the transmittance value, from 3.7 W/( m2K) to 2.2 W/( m2K). on the other hand, the horizontal shadings allow guaranteeing the lighting and thermal indoor comfort.  Results demonstrated that the combination of both solutions provides a reduction of the Operative Temperature (OP) inside the office, chosen as a case study. The shading system, instead, was useful to control the levels of the illuminance, guaranteeing a balanced internal comfort.

The application of the IMM methodology, integrated and extended in this work, shows its flexibility to be adapted and used to evaluate also other academic campuses. Future developments will be focusing on the modification of the Incidence Matrix, avoiding some qualitative weights and transforming them into quantitative ones.

# Chapter 2

# SMART METHODOLOGY DEVELOPMENT: QUANTITATIVE INCIDENCE MATRIX METHOD (QIMM)

## 2.1 Introduction

The power of attraction of living in cities has exponentially increased in the last decades. Nowadays, for the first time in the history of the world, more people are living in urban contexts than in rural areas [36, 37]. This attractiveness is due to the fact that economies in urban context reach their highest level of productivity, guaranteeing cultural, social and economic benefits to citizens [38]. On the other side, growing urbanization is also the cause of several problems, such as pollution, resource consumption, social inequality and others. Just to give a couple of figures, cities today is responsible for the 80% of greenhouse gas (GHG) emissions and the 80% of the world's resources consumption [39]. Consequently, due to these emerging challenges, city planning deals no more to the design of buildings and infrastructure only, but also to the definition of a holistic vision where new issues as digitalization, integration, quality of life, citizen needs, and equality must be taken into account [41]. The Smart city model emerged in the 1900s as an alternative and innovative concept for city planning. Till now the concept has evolved and got complex [42,43,44] including multidisciplinary aspects and assets [45,46] and aiming to find a balance between benefits and costs for the main stakeholders involved (people, institutions, industry, universities, and companies) [47]. This complexity resulted in a lack of consensus about the Smart definition [48,49] and about the way to translate the ideal model into practical applications [50,51,52]. A wide literature research is indeed available, proposing different definitions, conceptual models and approaches to the development of the Smart City concept [53,54]. Regarding the definitions, a group of literature research focuses on the use of ICT and modern technologies as the main driver to the smart city development [55,56]. Other studies underline the importance of human capital, city services and participation for improving economic, social and environmental aspects of a Smart city [57,58].

## 2.2 State of art: Smart City models and approaches

Regarding the models and approaches, a considerable group of literature studies focused on the development of evaluation frameworks for the smart city performance assessment, both from the qualitative and quantitative perspectives. Among them the first one was proposed by [59] where the level of Smartness of 70 European medium sized cities is evaluated based on their performance in six main axes. More recently, the authors of the work [60] developed a measurement tool for assessing smart performance, identifying six layers of a smart city. In [61] a fuzzy procedure is applied for identifying the weights of different Smart indicators, which are used for the creation of a unique "smart city index". In this framework, a useful report was developed by [49], called "Mapping Smart Cities in the EU" in order to collect all the smart city projects and models in Europe, highlighting their performances especially with the respect to Horizon 2020 objectives.

Moreover, interesting researches are available proposing qualitative planning methods. These studies are not aimed to evaluate the performance of a city but mainly to guide administrators in the identification of efficient Smart strategies to be applied in the real context. As an example, in the work of [62] a crowdsourcing approach was used to collect the most common smart services and to define a Smart City Transformation Framework (SCTF) for the deploying of smart interventions. In [11] an innovative and multidimensional methodology is provided, which is based on the analysis of the mutual impacts among strategies belonging to different smart axes by means of the "synergy" concept. Similarly, The "intelligenter method" [63] is based on the creation of multi-subsystem collaborations that provide better results in terms of efficiency in the use of natural and economic resources: this is called "Collaborative Sub-Systems" and it is based on the holistic and systemic approach of the urban context. Finally, the work of [64] proposed a multilayer approach based on systems theory and it was used to envision how Spanish cities could evolve in the horizon 2030. Other researches applied triple helix conceptual model to assess the role of different stakeholders in the planning phase of the Smart cities [65,66]. Stakeholders involvement has indeed recently begun a hot topic in literature: many studies evidenced the need of taking into account the stakeholders' opinion for an efficient urban transformation [67, 68, 69, 70].

This brief overview of the Smart city vision highlights that, besides the variety of approaches, there is still the need for the development of quantitative approaches able to put the smart city theory into practice and to apply a global and holistic view in the planning phase. According to this, scientists propose models as much as possible integrated, comprehensive and multifaceted; practitioners on the other side have to face with the limitations of implementing visionary projects in the real context, preferring therefore to work on sector-based interventions instead of integrated strategies [71, 67, 41]. The presence of those two opposite approaches, highlighted by [71] is still a concrete limitation for a holistic and integrated smart city realization. Current Smart applications frequently uses top-down approaches , as it can be noticed for the 15 major cities described by [67]: those smart planning projects are mainly focused on the ICT aspect and this is considered as the principal driver for pushing improvements in urban systems. This is clearly in contrast with the Smart City concept, that aims to promote the application of both top down and bottom-up approaches, starting from a global view of the urban context [41].

There is therefore the need to fill the gap between theory and practice proposing "practical planning methodologies" which can help in choosing, prioritize and control the performance of the Smart strategies implemented in the urban contexts [11, 72, 73] from an holistic perspective, as scientist suggest [74].

An important example is the work of [71], that proposes a tool called Smart City Projects Assessment Matrix. It is a holistic framework for developing smart city projects and assessing urban challenges in each region Moreover, this methodology was applied on the South and East Mediterranean Region at both the regional and project levels. Another example is the ASEAN Smart City

Network (ASCN) project that has the aim to transform 26 cities into smart contexts. This project provides a digital platform in which designers and policies can disseminate and promote initiatives [75]. Finally, the Institute of Technology, Bandung (ITB) developed the Garuda Smart City Framework (GSCF), a methodology that consists in different steps, including city measurement model, smart city Architecture, standard and services [76]. In this case the technological aspect is recognized as one of the main driver for smart city. This planning method aims to highlight the importance of innovative, technology and integrated solutions for improving the quality of life.

Starting from this point, the present work is in line with the targets of those projects, since the aim is to reduce the gap between theory and practice of Smart City, providing quantitative and integrated methodologies for the transformation of real case studies.

This work therefore proposes a new quantitative method based on a previous qualitative model developed by the same authors [11, 72]. The feasibility and validity of the method will be tested through the comparison with an existing AHP model and the application of both approaches on two real case studies, characterized by different territorial dimensions. Both the new and the AHP methods belong to the group of the MADM models; these models can be very suitable for the assessment of the best smart strategy among a set of different proposals, thanks to their capability of prioritization and scoring.

Quite few studies in literature applied the MADM models for city planning,, either for the development of the Smart cities [77] or for the assessment of urban sustainability level [78]. An exception is the work of [66], in which authors decide to use the Analytic Network Process (ANP), an advanced version of the Analytic Hierarchy Process. As highlighted by [66], the network nature of the city should be described through a realistic model based on a network system, which allows to guide the interactions and to provide feedback within all the elements. A more detailed description of the MADM models and their potentialities is provided in the following paragraphs.

## 2.3 Aims and Methodology

At the best of author's knowledge, there are not studies in literature comparing two quantitative planning models. Therefore, in this work the comparison of the two methods allows to:

- Validate the methodological approach developed by authors, through the comparison with an existing AHP method and the application of both the models on two real case studies, characterized by different territorial scales.
- Highlight the differences and similarities between the two methods
- Compare the final rankings and assess the impacts of the modelling process on the identification of the most performing strategies
- Identify limits, strengths and potentials of the proposed methodology.

The new methodology proposed in this work is called Quantitative Incidence Matrix Method (QIMM), which is an evolution of a matrix method (IMM) firstly elaborated in previous papers of the same research's team [11, 72]. The QIMM is validated trough the comparison with another MADM approach: a modified version of the Analytic Hierarchy Process (AHP) [79], called Hybrid AHP, which was developed by the University of Palermo in [80].

One of the most important aspects of those two methods is their flexibility: the number of smart city fields, actions and indicators can be changed from time to time, depending on the characteristics of the case study. The core of the two methods lays in the capability of putting the different actions in relation to each other to understand the mutual impacts and establish the priorities of the actions in an integrated way: this is actually one of the main target of a Smart city. Those two methods will be applied to two different case studies, in order to verify if and to what extent the results are similar and how this would change the strategy decision making.

The first case study is the Sicilian residential building sector's EEMP (Energy and Environmental Master Plan developed by the Sicilian Region) and the second one is the Palazzo Baleani, a building in the city centre of Rome, that is owned by Sapienza University.

The application of the Hybrid AHP method to the Sicilian case district was originally developed by [80]: in the current work, authors therefore limit to describe and reproduce what was originally done in that paper. Conversely the application of the Hybrid AHP method to Palazzo Baleani, the application of the QIMM to both the Sicilian district and Palazzo Baleani, the comparison among all the results is an original work of the authors.

Those two cases study represent two different configurations, on one hand the entire Sicilian building sectors and on the other hand a single historical building. The flexibility of those methods is demonstrated due to the different case studies scale application: macro scale as district and micro scale as the single building.

## 2.4 Description of the smart methodology (QIMM)

### 2.4.1 MDMA and QIMM relation

Multi-criteria analysis is a decision-making tool based on the quantitative analysis of the strengths and weaknesses among heterogeneous criteria of a certain proposed strategy. Following the classification made by [81], MADM is one of the two branches of Multiple - Criteria Decision Making (MCDM), which transforms the real-world problems into continuous or discrete systems. MADM allows to reproduce discrete problems, considering a limited number of alternatives not measurable in a single dimension. More in detail, MADM consists of a group of operations for ranking and scoring multiple alternative solutions usually characterized by contrasting attributes [82]. MADM is composed by a matrix, called decision matrix, which describes the contribution of each alternative against each attribute. Two operations are generally required to calculate this matrix: scoring and weighting. The first one involves assigning a numerical value to each attribute contributions, within a preference scale. The weighting, instead, consists in identifying a weight for each attribute. Consequently, a MADM method provides an explicit weighting system for the different criteria in order to estimate the correct weight. The QIMM can be included in the MADM methods, due to its typical structure of matrix weighting process.

### 2.4.2 Quantitative Incidence Matrix Method (QIMM)

The flowchart of the original method IMM includes different steps: data collection, performance indicators analysis, actions strategies elaboration and their mutual impact on the smart fields [11, 72]. The phase involving the identification of the best fitting strategy is represented by the Incidence Matrix, that establishes in a qualitative way, the influence of each actions on the smart aspects. According to this, it is possible to obtain the best action for each smart field. The last step is to simulate the winner actions and implement them on the urban context.

Starting from this methodology, some important modifications are carried out in order to transform this qualitative method into a quantitative one. Moreover, those modifications allow users to apply this new methodology for both planning and ex-post analysis.

Three main difference can be noticed in the modified method:

1) All the strategies are simulated in the first phase. It allows to obtain quantitative results in different fields (Mobility, Community, Environment, Energy and Economy) represented by specific Smart Indicators, belonging to the various Smart fields.
2) The assessment of the impact of each strategy in the incidence matrix is developed by means of quantitative Smart performance indicators (in substitution of the qualitative Synergy scores) and quantitative additional weights. The standardisation of those indicators is based on a common process, which uses standard normalization criteria.
3) In the transformation of the method from qualitative to quantitative, the Users score was no more taken into consideration due to the complexity in collecting and quantifying stakeholders' opinions.

This variation in the method allows to fill the gaps highlighted in the previous approach proposed by the authors [73].

Figure 14 shows the flowcharts of both methods and their differences.

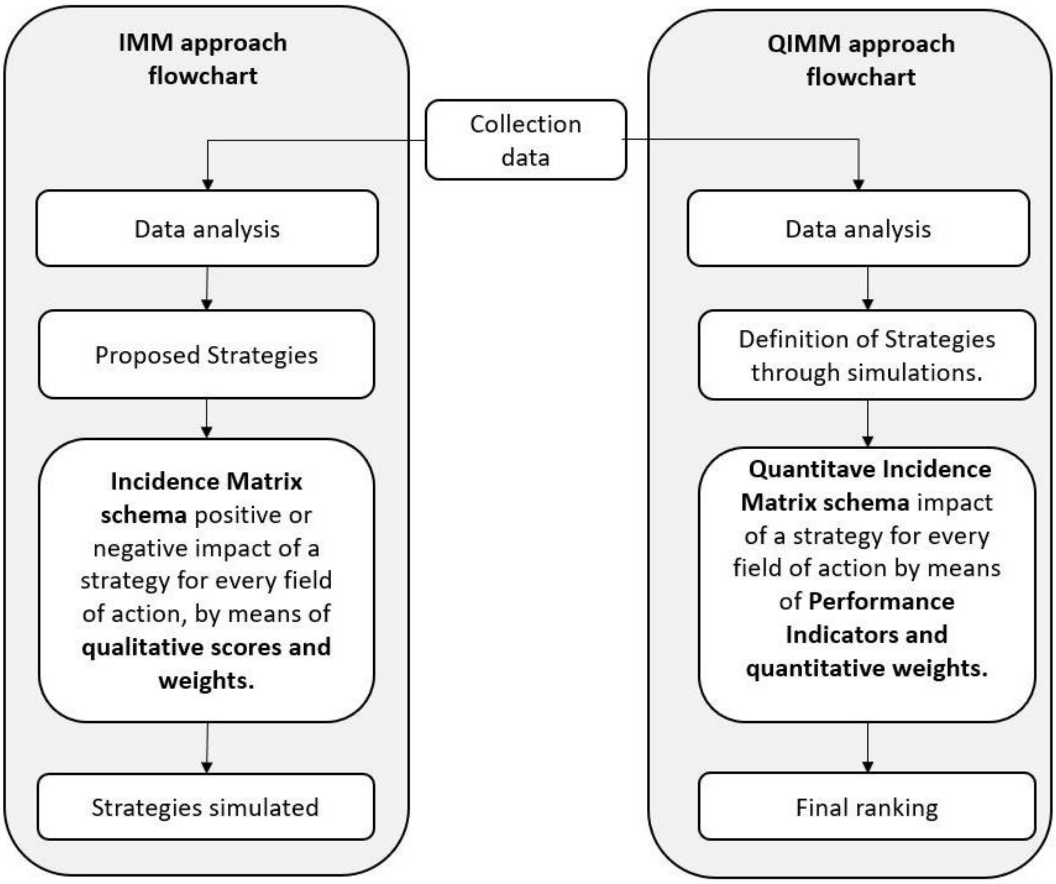


Figure 14: Elaboration of QIMM procedure

Following, authors provide a deep explanation of each step of the presented method.

- **Generate matrix**

In the QIMM method a single matrix is used, which contains all the indicators that need to be measured for every intervention. A segmentation is recommended in order to make it easier to read, but it will not affect the results. An example can be seen below:

Table 14: Sample of Incidence matrix

| **Field of action** | **Index** | **Action 1** | **Action 2** | **Action3** |
|---|---|---|---|---|
| Energy | Gross primary energy consumed (ktoe/year) | $En1_1$ | $En1_2$ | $En1_3$ |
| | Energy produced by renewable resources (%) | $En2_1$ | $En2_2$ | $En2_3$ |

|  |  |  |  |  |
|---|---|---|---|---|
| Environment | Tons of CO2 produced | $Env1_1$ | $Env1_2$ | $Env1_3$ |
| Economy | Total investment cost (€) | $Ec1_1$ | $Ec1_2$ | $Ec1_3$ |
|  | Rate of return (%) | $Ec2_1$ | $Ec2_2$ | $Ec2_3$ |
| Mobility | Time saved to arrive to office (min) | $Mob1_1$ | $Mob1_2$ | $Mob1_3$ |
| Community | Thermal comfort index (%) | $Com1_1$ | $Com1_2$ | $Com1_3$ |

The magnitudes corresponding to the effect of the actions against the proposed indicators will be determined through simulations, which will evaluate how the proposed actions perform under the examined conditions. It is important to verify the capacity of the simulation software and the data availability at this point as if the results cannot be trustfully measured by the indexes, these should be adjusted accordingly.

- **Distance to mean normalization**

For the normalization and scaling method, the "distance to mean" method has been chosen. A similar method to those proposed in the OECD Handbook [22] and in the work of [72]. Firstly, the mean for every indicator has to be calculated.

$$M_i = \frac{\sum_{j=1}^{n} x_{ij}}{n}; for\ i = ind1, ind2, ind3 \ldots m$$

Equation 5.

Where, $i$ will be the indicators and $j$ will be each of the actions, $m$ will be the total indicators and $n$ stands for the total amount of actions suggested. Now, the distance to the mean is calculated for every indicator, using the following equation:

$$a_{ij} = \frac{x_{ij} - M_i}{M_i}$$

Equation 6.

- **Scaling**

After using Equation 6 for all the actions, a scaling factor needs to be added in order to be able to effectively compare all indicators. The scale will be set by using the maximum and minimum magnitudes for every action. The spaces between the limits will be divided in 10 ranges, which will be assigned a score from -5 to 5. The score ranges will be set in such a way that if the action magnitudes are less than 0, they will be set with a score of 0 or below. This means that for negative scores there will be 6 ranges, while for positive ranges only 4. This distribution was made in order to benefit the alternatives that have a higher performance in the indicators. Two different equations will be needed in order to set the limit value for every range:

$$\begin{cases} x_{s+1} + \left|\frac{x_{min}}{5}\right| ; for\ s > -4 \\ x_{s-1} + \left|\frac{x_{max}}{4}\right| ; for\ s > 0 \end{cases}$$

Equation 7.

Where $s$ refers to the score, and $x_{min}$ refers to the minimum and $x_{max}$ refers to the maximum magnitude of the actions. This procedure has to be repeated for all indicators of interest until the matrix is completely normalized and scaled.

- **Correction Factor**

A correction factor has been included to balance the positive and negative magnitudes of the indicators. In some cases, the indicators will measure changes that the higher they get, the higher the project will get benefits. The opposite situation can also happen, where the higher magnitude of the indicator would affect the project negatively. According to this, a correction factor of -1 or 1 was introduced in order to establish the correct interpretation of the indicators. This correction factor is given by the interpretation of the designers and could be avoided if the indicators are properly selected. An example will be given assuming two different indicators from an energy efficiency project:

Table 15: Example of correction factor

| **Indicator** | **Correction factor** |
|---|---|
| **Gross Energy Consumption (ktoe/year)** | -1 |
| **Economic savings (€/year)** | 1 |

In the example shown in Table 15, it can be seen how correction factor is applied. When Gross Energy Consumption indicator increases means that more energy will be consumed per year, which will be an undesirable behaviour for the aims of a project that aims to increase energy efficiency. On the other side, when the Economic Savings indicator increases it will represent a benefit as it means less money will be spent, which is the objective of energy efficiency projects.

- **Economic and time feasibility**

Two additional scores are going to be considered and summed separately from the previously calculated indicators. The assignment of the scores will be determined between 0 and 1 depending on the amount of time and money spent for every intervention. The most expensive interventions got the lowest score of 0, while those most cheap were assigned a score of 1. A similar approach was used for time, where the actions that needed more time to be completed were assigned a value of 0, while those that were installed the quickest had a score of 1. The values in between were given a score according to their value respect to 1. Equation 8 shows the process for assigning the scores to all the intermediate interventions which are neither the cheapest nor the most expensive.

$$x_i = 1 - \left(\frac{c_i}{max[c_i, c_n]}\right) for\ i = 1, n$$

Equation 8.

An example can be seen below in Table 16:

Table 16: Example of time score

| Action | Time to install (h) | Score |
|---|---|---|
| Action 1 | 30 | 0.33 |
| Action 2 | 15 | 0.67 |
| Action 3 | 3 | 1 |
| Action 4 | 45 | 0 |

The magnitude of the score (between 0 and 1), was assigned targeting to avoid a big change in the final ranking. The use of these weights is intended to show the contribution of aspects that are considered important for any project to be developed, independently from which indicators are being measured.

### 2.4.3 Hybrid AHP method

A specific modification of the AHP method was proposed in [80] called "Hybrid AHP". The main difference with the AHP method is the way the data is aggregated from the base level of "action" to the intermediate and higher levels. The scheme, shown in Figure 15, describes the four levels used in this method and their significance. This hybrid scheme has been also applied in literature in the works of [83] and [84]; it allows to give high relevance to the judgments of the stakeholders related to the selected indicators during the evaluation process. The addition of the stakeholders' opinion is relevant and in line with the latest literature studies, which go in the direction of including all the users and actors in the planning process. Nevertheless, it could imply the addition of a certain subjectivity in the model that should be carefully managed. The comparison of the two methods is a useful way to assess how much this subjectivity influence the final results. This aspect will be further discussed in the conclusion section.

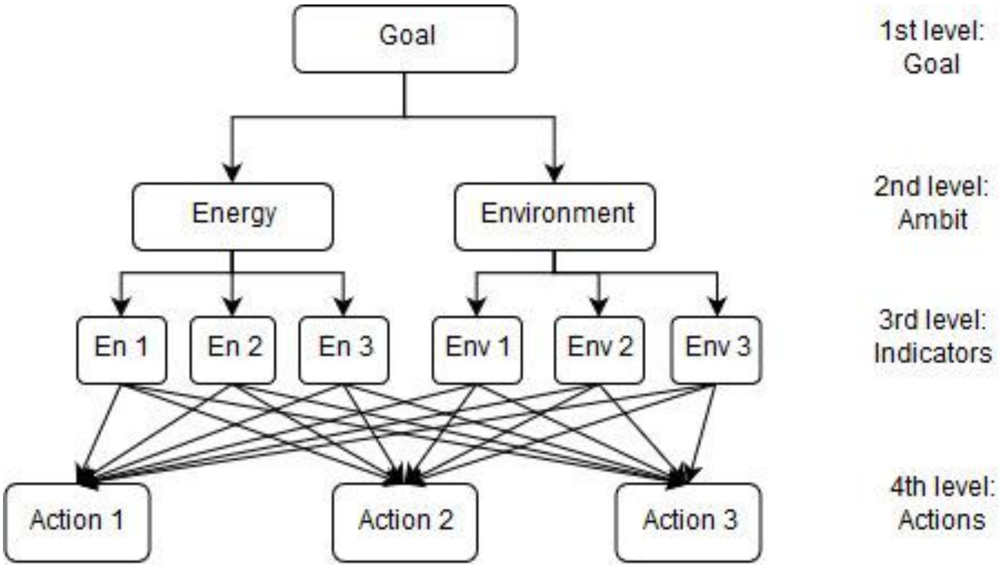


Figure15: Hybrid AHP scheme

The 1st level is the Goal, which is the target that must be reached. The 2nd level, refers to each ambit, which means to the main topic the indicators can be grouped on. In case of Figure 15, the example was given using only energy and environment. However, this model is flexible since the number of main topics and indicators can be changed as needed, including other smart axes such as People & Living, Economy, and Mobility. The weight used for the aggregating data at 2nd level is given by the number of indicators measured for each ambit divided by the total amount of indicators. Referring to figure 15, the weight for the "Energy" ambit is 0.5 as it is composed by 3 indicators while the total number of indicators is 6. The 3rd level weight is given by the stakeholders. It refers to how favourable would they be to one indicator respect to the others in the same ambit. People were therefore asked to select which indicator was the most important for each ambit; from the votes, the percentage influence of each indicator in relation to its own ambit was assessed. A hypothetical voting process can be seen below, assuming 30 people voting for the energy indicators:

Table 17: Hypothetical voting of indicators

| **Indicator** | **EN 1** | **EN 2** | **EN 3** |
|---|---|---|---|
| Votes | 20 | 2 | 8 |
| Percentage % | 66 | 7 | 27 |

The weight for each indicator is given by the percentage respect to the total voters. In the 4th level the pairwise comparison among actions is made by using eigenvalues. Firstly, a square matrix for every indicator is needed, where the size is determined by the amount of actions to be analysed (3 in this example). Which means, a total of 6 matrices sized 3x3. Taking for example the indicator En1, using magnitudes of each action represented as a variable ($A_x$), the generated matrix has the following shape:

Table 18: Ratio matrix for EN 1

| | **Action 1** | **Action 2** | **Action 3** |
|---|---|---|---|
| **Action 1** | 1 | $A_1/A_2$ | $A_1/A_3$ |
| **Action 2** | $A_2/A_1$ | 1 | $A_2/A_3$ |
| **Action 3** | $A_3/A_1$ | $A_3/A_2$ | 1 |

Then, local values are calculated, by using the equation:

$$v_n = \sqrt[m]{a_{n1} * a_{n2} * \ldots * a_{nm}}$$

Equation 9.

Where n = m as they represent the number of criteria that will be evaluated. Looking at **Errore. L'origine riferimento non è stata trovata.**, the following igenvector component values, $v_i$ can be obtained:

$$v_1 = \sqrt[3]{A_{11} * A_{12} * A_{13}};\ v_2 = \sqrt[3]{A_{21} * A_{22} * A_{23}};\ v_3 = \sqrt[3]{A_{31} * A_{23} * A_{33}}$$

Equation 10.

where the values $A_{nm}$ refer to each element of the matrix, *n* referring to the row number, and *m* to the column number. Now, each eigenvector component is divided by the sum of all of them, as stated by those normalization equations:

$$S = \sum_1^n v_i \quad ; \quad x_n = \frac{v_n}{S}$$

Equation 11.

Equations below show the solution for this example:

$$S = v_1 + v_2 + v_3$$

$$x_1 = \frac{v_1}{S};\ x_2 = \frac{v_2}{S}\ ;\ x_3 = \frac{v_3}{S}$$

Equation 12.

In this way, the normalized values for the EN 1 for every action can be obtained. This is used as the local weight $L_{4,EN1}$, to be aggregated with the other weights in order to obtain a score, as it can be seen below:

$$G_{Action1,EN1} = L_{4,EN1} * L_3 * L_2$$

Equation 13.

Where, the $L_3$ and $L_2$ values stand for the 3rd level weight and 2nd level weight. Checking at **Errore. L'origine riferimento non è stata trovata.** it can be found $L3 = 0.67$ and $L2 = 0.5$ as previously stated. The process must be repeated for every indicator, which leads to the equation:

$$G_{Action1} = \sum_{i=EN1 \div ENV3}^{6} G_{Action1,i}$$

Equation 14.

Equation 14 must then be repeated for every action. When all the final scores of all actions are calculated, a ranking is created by which an optimal action can be selected for the required goal. More detailed information regarding the Hybrid AHP method can be found in the paper of [80].

Finally, in order to properly compare the two methods, authors made a single modification in the Hybrid AHP process proposed by [80], adding the correction factor at the Goal level calculation (1st level of the method).

## 2.5 Case study

### 2.5.1 Sicilian residential district case study

This case study comes from the work of [80], whose objective was to analyse the strategies implemented by a Residential Sector Master Plan using the Hybrid AHP method. The Residential Sector Master Plan aimed to optimally distribute the available economic resources of the region for the development of sustainable interventions supported by building owners. However, the opinion of the stakeholders in the definition of the indicators that would measure the effectiveness of the interventions was originally missing. The indicators used for selecting the interventions were mostly referred to as economic issues: €/toe and €/$t_{CO2}$. The authors of the paper [80] decided, therefore, to study how the priority of the interventions would have changed if the indicators would have been weighted considering the opinion of the stakeholders. The votes from the stakeholders are presented in the work of [80]. In Tables 19 and 20, the interventions and their respective indicators are shown. Input data referred to these interventions are available in the original paper of [80].

Table 19: Indicators for the Sicilian District (from [80])

| **Indicators/ Actions** | **A** | **B** | **C** | **D** | **E** | **F** | **H** | **I** | **J** | **K** |
|---|---|---|---|---|---|---|---|---|---|---|
| **EN1** | 1311 | 1297 | 1312 | 1294 | 1305 | 1306 | 1305 | 1311 | 1276 | 1298 |
| **EN2** | 26.4 | 26.10 | 26.40 | 26.10 | 26.30 | 26.30 | 26.30 | 26.40 | 25.70 | 26.10 |
| **EN3** | 58460 | 98353 | 122442 | 555399 | 289993 | 54495 | 59915 | 60314 | 820000 | 94000 |
| **ENV1** | 135627 | 228181 | 397937 | 1805047 | 922980 | 177110 | 476331 | 196022 | 2665000 | 305500 |
| **ENV2** | 0.092 | 0.091 | 0.092 | 0.091 | 0.091 | 0.091 | 0.09 | 0.092 | 0.09 | 0.091 |
| **EC1** | 0.0023 | 0.0063 | 0.0015 | 0.0074 | 0.0055 | 0.0028 | 0.0178 | 0.0016 | 0.0292 | 0.0094 |
| **EC2** | 0.0053 | 0.0146 | 0.0048 | 0.024 | 0.018 | 0.009 | 0.1418 | 0.0054 | 0.0689 | 0.0209 |
| **EC3** | 0.0004 | 0.0008 | 0.0007 | 0.0035 | 0.0026 | 0.0003 | 0.0022 | 0.0003 | 0.01 | 0.0012 |
| **EC4** | 192343 | 312234 | 564441 | 5315291 | 3237806 | 0 | 111992 | 274157 | 3760000 | 480000 |

Table 20: Reference letters and interventions

| **Reference** | **Interventions** |
|---|---|
| **A** | Replacing electric boilers with natural gas boilers |
| **B** | Replacing gas fired water heater with open chamber and pilot flame with sealed chamber and electronic ignition |
| **C** | Replacing single-window glasses with double - window glasses |
| **D** | Building envelope insulation |
| **E** | Roof insulation |
| **F** | Replacement of electric and electronic household appliances |
| **H** | Replacing electric water heaters with methane water heater |
| **I** | Installation of high efficiency air conditioning systems |
| **J** | Solar thermal collectors |
| **K** | PV panels |

Finally, below are reported indicators calculated by [80] and their significance.

Table 21: Indicators selected by Stakeholders1

| Indicators | Description |
|---|---|
| **EN1** | Final uses gross energy consumption (ktoe/year) |
| **EN2** | Energy intensity of the residential sector (toe/M€) |
| **EN3** | Saved energy during the life span of proposed action (toe) |
| **ENV1** | CO2 emission avoided through lifespan of proposed action (tCO2) |
| **ENV2** | Emission intensity (tCO2/M€) |
| **EC1** | Average cost of one saved toe (€/toe) |
| **EC2** | Average cost of one tCO2 (€/t CO2) |
| **EC3** | Average cost of one toe saved during the lifespan of the action (€/toe) |
| **EC4** | Increase in number of working hours |

The data for the indicators was obtained from simulations for each intervention, throughout the years of 2004 to 2012.

### 2.5.2 Palazzo Baleani case study

In order to verify the applicability of the proposed Quantitative Incidence Matrix (QIMM) method, a real case study located in Rome was chosen. It is a typical historical building, called Palazzo Baleani, which was built in the sixteenth century. Currently, the biggest part of the building is owned by the Sapienza University of Rome and the spaces are mainly used as classrooms and offices. The study started with an analysis of the state of the art of the building. The main data about the building, such as dimensions, construction materials, electrical and thermal loads were gathered or simulated using engineering software [85]. As expected for an old building, the inefficient envelope and windows greatly impact on the cooling and heating consumption. However, the age and relevance of the building limit the possibilities of refurbishment and the addition of technical and technological devices, especially on the façade, according to the current Standard [86,87]. Similarly, the installation of PV panels is forbidden, because they can affect the appearance of the building. Considering these restrictions, the improvement due to the implementation of selected interventions was calculated, as showed in the work of [85]. Few

---

indicators were defined for measuring the impact of the interventions on several Smart fields (Energy, Economy, Environment, Community). The final list of interventions can be seen in Tables 22 and 23. In Table 22, the cells highlighted in grey show that in a few cases the results are negative. These values were substituted with zero by the authors to properly apply both QIMM and AHP methods to this case study since the AHP cannot process negative values.

Moreover, four of the strategies are alternative [85]. The method can be indeed used to assess if it would be preferable to install a traditional photovoltaic system (PV A) or the photovoltaic roof tiles (PV B). Similarly, it can also be used for choosing between COOL 1 and COOL 2:

- COOL 1: The installation of four heat pumps at Variable Refrigerant Flow which supply indoor air conditioning units in offices, school rooms and conference rooms
- COOL 2: The installation of an air handling unit and an inverter heat pump for conditioning the entire building, taking advantage of the existing air ducts and an absorption chiller.

Intervention on windows regards the addition of a supplementary internal glass to the existing windows in order to create an air gap of 20 mm and reduce the thermal transmittance; the Energy Management System (EMS) allows to monitor and manage loads of the building to reduce consumption and optimize electricity peaks; intervention on the solar heating system (SHS) consists in the substitution of the broken collectors already placed on the roof of the building and to reactivate the entire system; regarding the lighting systems, the two mono-lamp fluorescent tubes installed in the ceiling fixtures are replaced with LED tubes.

The other strategies (T, E, T-E, T-D, E-D, T-E-D) are combinations of the aforementioned strategies. By applying the two methods it will be therefore interesting to assess if it is more efficient to develop single or combined strategies from a holistic perspective.

Table 22: List of indicators and strategies

| | Strategies | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Indicators** | **Wind.** | **Col1** | **Col2** | **PV A** | **PV B** | **EMS** | **SHS** | **Light** | **T** | **E** | **T-E** | **T-D** | **E-D** | **T-E-D** |
| **En1** | 20.8 | 25.9 | 24.8 | 42.1 | 41.3 | 43.4 | 44.9 | 43.7 | 32.8 | 37.0 | 23.1 | 30.9 | 36.6 | 21.6 |
| **En2** | 417 | 648 | 621 | 842 | 826 | 1301 | 1123 | 1310 | 656 | 924 | 461 | 618 | 914 | 431 |
| **En3** | 0.16 | 0.19 | 0.24 | 0.09 | 0.11 | 0.08 | 0.03 | 0.07 | 0.29 | 0.20 | 0.50 | 0.33 | 0.20 | 0.53 |
| **Env1** | 97 | 106 | 101 | 95 | 93 | 98 | 106 | 98 | 94 | 82 | 61 | 93 | 81 | 57 |
| **Env2** | 0.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 1.00 | 1.00 | 0.00 | 1.00 |
| **Ec1** | 51 | 138 | 109 | 309 | 256 | 309 | 1323 | 339 | 216 | 52 | 83 | 114 | 149 | 31 |
| **Ec2** | 3491 | -24 | -24 | 866 | 896 | 4950 | 30296 | 5428 | 1661 | 691 | 745 | 658 | -2412 | 211 |
| **Com 1** | 1.29 | 0.82 | 0.82 | 0 | 0 | 0 | 0 | -0.01 | 0.88 | -0.01 | 0.88 | 0.88 | -0.04 | 0.88 |
| **Com 2** | 0.53 | 0.63 | 0.63 | 0 | 0 | 0 | 0 | -0.03 | 0.67 | -0.03 | 0.66 | 0.66 | -0.03 | 0.66 |

Table 23: Reference abbreviation of interventions

| **Actions** | **Alternative** |
|---|---|
| **A** | Windows refurbishment |
| **B** | Improvement of the cooling system (type A) |
| **C** | Improvement of the cooling system (type B) |
| **D** | Photovoltaic System |
| **E** | Roof tiles Photovoltaic System |
| **F** | Energy management system |
| **G** | Solar Heating System |
| **H** | Light fixtures replacement |
| **I** | Thermal (COOL2 +Windows) |
| **J** | Electric (PV A + Management system+ Light) |
| **K** | Thermal + Electric |

| | |
|---|---|
| **L** | Thermal + Solar Heating System |
| **M** | Electric + Solar Heating System |
| **N** | Thermal + Electric + Sanitary hot water |

Below are reported the indicators chosen for this case study analysis.

Table 2: Indicators used for the Matrix Method

| Nomenclature | Indicator |
|---|---|
| **En1** | **Gross Energy Consumption (toe/year)** |
| **En2** | **Energy Consumption on lifespan (toe/year)** |
| **En3** | **Primary Energy Index (%)** |
| **Env1** | **Annual CO2 emissions (tCO2)** |
| **Env2** | **Local pollution index (%)** |
| **Ec1** | **Average cost of toe saving (€/toe*year)** |
| **Ec2** | **Average cost of CO2 saving (€/tCO2)** |
| **Com1** | **Thermal comfort index (%)** |
| **Com2** | **Thermal dissatisfaction index (%)** |

## 2.6 Results

### 2.6.1 Sicilian residential district case study: QIMM method application

In this sub-section, the QIMM is applied to the Sicilian residential district. In order to explain each step of the method, authors decided to describe the process for a single action, knowing that it is repeated for all the strategies shown in Table 20. In this case, the Correction Factor has been defined based on the indicator's interpretation given in [80].

More in detail, EN1 is negative since it represents the total energy consumption per year; EN2 is positive since it is the efficiency used for a country to convert the Gross Domestic Product into energy commodities; EN3 is positive since it represents the total energy saved in one year; both the environment indicators

(ENV1 and ENV2) are positive and represent savings in $CO_2$ emissions; EC1, EC2 and EC3 are considered negative since they quantify the average expenses per toe and $CO_2$ and finally EC4 is positive since, as said in [80], it represents the number of new jobs created by the realization of each intervention.

An example of the QIMM application is shown for action A (Table 26):

Table 26: Example of QIMM process for Action A

| | | **Action A** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Indicators** | | | | | | | | |
| | | **EN 1** | **EN 2** | **EN 3** | **ENV1** | **ENV2** | **EC1** | **EC2** | **EC3** | **EC4** |
| **L3** | Distance to mean | 0.72 | 0.72 | -73.59 | -81.45 | -0.99 | -72.55 | -83.05 | -81.82 | -86.5 |
| | Score | 4 | 5 | -4 | -5 | -5 | -4 | -4 | -4 | -4 |
| | CF | -1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 | 1 |
| | Sum | -5 | | | | | | | | |
| **L2** | Time feasibility | 0.83 | | | | | | | | |
| | Economic feasibility | 0.30 | | | | | | | | |
| **L1** | TOTAL | -3.87 | | | | | | | | |

As noticeable in Table 26, the level L3 includes the "distance to mean" normalization and the CF assignment; the level L2 regards the weighting process with the addition of the scores "Economic feasibility" and "time feasibility"; the level L1 finally allows to get the score of each action. As aforementioned in this method, the scaling process for score assignation can be adjusted to the magnitudes that are being worked with. In this work, authors propose a score range between -5 and 5 and the exemplificative results are shown in Table 27. As an example for EN1, since the distance to mean for EN1 is 0.72, which is comprised between 0.60-0.80 according to this scaling, the score assigned is 4.

Table 27. Example of scaling factor of EN1 indicator

| **EN1** | | |
|---|---|---|
| **score scaling** | **min** | **max** |
| **-5** | -2.0 | |
| **-4** | -1.98 | -1.58 |
| **-3** | -1.58 | -1.19 |
| **-2** | -1.19 | -0.79 |

| | | |
|---|---|---|
| **-1** | -0.79 | -0.40 |
| **0** | -0.40 | 0.00 |
| **1** | 0.00 | 0.20 |
| **2** | 0.20 | 0.40 |
| **3** | 0.40 | 0.60 |
| **4** | 0.60 | 0.80 |
| **5** | 0.80 | |

Then, reference case studies were chosen as base case examples to assess the time required for intervention, used in the calculation of the "Time feasibility score". An example of timing for a few actions is shown in Table 28 with the relative bibliographic sources.

Table 28: Estimated time for interventions

| Intervention | Time required | Source |
|---|---|---|
| **A** | 3 days/ floor | (1) |
| **B** | about 10 week | (2) |
| **C** | 15 windows per day | (3) |
| **D** | 25 days | (4) |
| **E** | 1 week | (5) |
| **F** | 5 days | (6) |
| **H** | 3 hours/ house | (7) |
| **I** | 4 days | (8) |
| **J** | 2 days | (9) |
| **K** | 2 days | (9) |

Regarding the economic feasibility, the investment costs of each intervention were available in the paper of [80]. Using these data on time and costs, the respective scores have been calculated, as shown in Table 29. The final ranking is shown in Table 30.

Table 29: Time and cost feasibility scores for the Sicilian residential district

| | Costs feasibility | | Time feasibility | |
|---|---|---|---|---|
| **Intervention** | **Total cost (M€)** | **Score** | **Hours** | **Score** |
| **A** | 192.3 | 0.30 | 288 | 0.83 |
| **B** | 156.1 | 0.44 | 1728 | 0.00 |

| | | | | |
|---|---|---|---|---|
| **C** | 276.5 | 0.00 | 384 | 0.78 |
| **D** | 250.7 | 0.09 | 600 | 0.65 |
| **E** | 171 | 0.38 | 168 | 0.90 |
| **F** | 196.4 | 0.29 | 120 | 0.93 |
| **H** | 33.9 | 1.00 | 1728 | 0.00 |
| **I** | 274.1 | 0.01 | 96 | 0.94 |
| **J** | 117 | 0.58 | 3 | 1.00 |
| **K** | 100 | 0.64 | 48 | 0.97 |

Table 30: Final Ranking for the Sicilian residential district applying the QIMM method

| | **QIMM** | |
|---|---|---|
| **Ranking** | **Actions** | **Score** |
| **1** | **D** | 6.74 |
| **2** | **E** | 3.28 |
| **3** | **C** | 1.78 |
| **4** | **I** | -2.05 |
| **5** | **J** | -2.42 |
| **6** | **A** | -3.87 |
| **7** | **F** | -4.78 |
| **8** | **B** | -8.56 |
| **9** | **K** | -11.39 |
| **10** | **H** | -22 |

Using this method, high relevance was attributed to the interventions on the building envelope actions D, E and C, which respectively regard: Building Envelope Insulation (D), Roof insulation (E), Replacing single-window glasses with double ones (C). These results underline that very high importance is given to those interventions regarding the refurbishment of the building envelope, which guarantees good energy and environmental performance with moderate economic expenses. Conversely, the last positions are occupied by the installation of PV panels (K) and the replacement of electric water heaters with methane water heaters (H).

### 2.6.2 Sicilian residential district case study: Hybrid AHP method application

This section describes the application of the Hybrid AHP method to the Sicilian district. Table 31 shows the results at each level of the method related to Action A. As aforementioned, in order to develop a correct comparison of the two methods, the Correction Factor (highlighted in grey in Table 31) was added in the Hybrid AHP procedure.

Table 31: Example of Local-global final table of each action.

| | **Action A** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Indicators** | **Eigenvalues** | **Stakeholders preferences %** | **Evaluation Ambits** | **Goal level** | | **Final score** | |
| | **L4** | **L3** | **L2** | **L1** | **Sum** | **CF** | **G** |
| **EN1** | 0.1 | 22 | 0.33 | 1 | 0.74 | -1 | 1.72 |
| **EN2** | 0.1 | 30 | | | 1.01 | 1 | |
| **EN3** | 0.03 | 48 | | | 0.42 | 1 | |
| **ENV1** | 0.02 | 67 | 0.22 | 1 | 0.28 | 1 | |
| **ENV2** | 0.1 | 33 | | | 0.74 | 1 | |
| **EC1** | 0.03 | 15 | 0.44 | 1 | 0.18 | -1 | |
| **EC2** | 0.02 | 15 | | | 0.11 | -1 | |
| **EC3** | 0.02 | 15 | | | 0.12 | -1 | |
| **EC4** | 0.02 | 55 | | | 0.43 | 1 | |

In the 4th level (L4), eigenvalues pairwise comparison is applied to the proposed interventions. Each indicator has a corresponding ratio matrix (as Table 32), with a total of 9 matrices.

Table 32. Example of Ratio matrix of each indicators

| | A | B | C | D | E | F | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| EN1 | 1 | 1.011 | 0.999 | 1.013 | 1.004 | 1.004 | 1.005 | 1.000 | 1.028 | 1.010 |
| | 0.989 | 1 | 0.989 | 1.002 | 0.994 | 0.993 | 0.994 | 0.990 | 1.017 | 0.999 |
| | 1.001 | 1.011 | 1 | 1.013 | 1.005 | 1.005 | 1.005 | 1.001 | 1.028 | 1.011 |
| | 0.988 | 0.998 | 0.987 | 1 | 0.992 | 0.991 | 0.992 | 0.988 | 1.015 | 0.997 |
| | 0.996 | 1.006 | 0.995 | 1.008 | 1 | 1.000 | 1.001 | 0.996 | 1.023 | 1.006 |
| | 0.996 | 1.007 | 0.995 | 1.009 | 1.000 | 1 | 1.001 | 0.996 | 1.024 | 1.006 |
| | 0.995 | 1.006 | 0.995 | 1.008 | 0.999 | 0.999 | 1 | 0.995 | 1.023 | 1.005 |
| | 1.000 | 1.011 | 0.999 | 1.013 | 1.004 | 1.004 | 1.005 | 1 | 1.027 | 1.010 |
| | 0.973 | 0.984 | 0.972 | 0.985 | 0.977 | 0.977 | 0.978 | 0.973 | 1 | 0.983 |
| | 0.990 | 1.001 | 0.989 | 1.003 | 0.994 | 0.994 | 0.995 | 0.990 | 1.017 | 1 |

Then, the eigenvectors are elaborated to obtain the normalized values of EN1 for every action, as shown in Table 33. Once the eigenvalues for each indicator are calculated, they are multiplied by both the weights of the stakeholders and the weights of each ambit to get the final score for a determined alternative.

Table 33. Example of eigenvectors calculation as local values.

| Indicator | Eigenvectors | | Eigenvectors (divided by the Sum) | Actions |
|---|---|---|---|---|
| EN1 | **v1** | 1.007 | 0.1007 | **A** |
| | **v2** | 1.00 | 0.100 | **B** |
| | **v3** | 1.01 | 0.101 | **C** |
| | **v4** | 0.99 | 0.099 | **D** |
| | **v5** | 1.00 | 0.100 | **E** |
| | **v6** | 1.00 | 0.100 | **F** |
| | **v7** | 1.00 | 0.100 | **H** |
| | **v8** | 1.01 | 0.101 | **I** |
| | **v9** | 0.980 | 0.098 | **J** |
| | **v10** | 0.997 | 0.100 | **K** |
| | Sum | 10 | | |

The votes from the stakeholders are reported in the work of [80] in Table 6. The total votes for each indicator are divided by the 67 voters of the ambit and multiplied by 100 to obtain the percentage weight. The number of indicators for each ambit is divided by the total number of indicators. According to this, the weights of the ambits are respectively: 0.33 for Energy, 0.22 for Environment, 0.44 for Economy. Final results are provided in Table 34.

Table 34: Final ranking for the Sicilian district applying the Hybrid AHP method

| | **Hybrid AHP** | |
|---|---|---|
| **Ranking** | **Actions** | **Score** |
| **1** | **D** | 15.12 |

| | | |
|---|---|---|
| **2** | **J** | 11.82 |
| **3** | **E** | 8.86 |
| **4** | **C** | 3.40 |
| **5** | **I** | 2.09 |
| **6** | **B** | 1.79 |
| **7** | **A** | 1.72 |
| **8** | **K** | 1.71 |
| **9** | **F** | 1.25 |
| **10** | **H** | -2.44 |

The rank shows that the most efficient solutions, occupying the first four positions, are the following: Building Envelope Insulation (D), Solar Thermal collectors (J), Roof insulation (E), Replacing single-window glasses with double ones (C). Intervention D got the same rank with both methods; conversely, intervention J achieved a better position compared to the ranking of the QIMM method (see Table 12). The last positions are occupied by the replacement of electric and electronic household appliances (F) and the replacement of electric water heaters with methane water heaters (H).

### 2.6.3 Palazzo Baleani case study: QIMM method application

In this section, the QIMM method is applied to the Palazzo Baleani. The process is the same as for the Sicilian residential district: performing normalization procedure; defining the scale factors; assigning the additional weights.

Regarding the interpretation of the indicators, the Correction Factor is assigned as follows: the energy ones (EN1 and EN2) are negative since they respectively represent the annual consumption in toe of each intervention and the total consumption of each intervention in its lifespan, while EN3 is positive since it is the savings in primary energy before and after the interventions. The ENVI1 environmental indicator is negative since it counts the amount of global emissions while ENV2 is positive since it represents the reduction of local pollution; similarly, the economic indicators are also negative, quantifying the expenses for savings one toe and one tonne of $CO_2$ per year. Finally, both the community indicators COM1 and COM2 express a positive impact, representing the improvements in thermal comfort and level of dissatisfaction before and after the intervention.

Table 35 shows the final ranking of the proposed QIMM approach.

Table 35: Example of QIMM process for Action A

| | | Action A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | INDICATORS | | | | | | | | |
| | | **EN 1** | **EN 2** | **EN 3** | **ENV1** | **ENV2** | **EC1** | **EC2** | **COM1** | **COM2** |
| **L3** | Distance to mean | -37.8 | -47.4 | -25.8 | 7.6 | -100 | -79.3 | -2 | -180 | 67.1 |
| | Score | -5 | -5 | -1 | -1 | -5 | -4 | 0 | 5 | 3 |
| | CF | -1 | -1 | 1 | -1 | 1 | -1 | -1 | 1 | 1 |
| | Sum | 14 | | | | | | | | |
| **L2** | Time feasibility | 0.00 | | | | | | | | |
| | Economic feasibility | 0.87 | | | | | | | | |
| **L1** | TOTAL | 14.87 | | | | | | | | |

As Table 35 shows, the entire process of normalization is applied to each indicator, using the distance to mean methods. Therefore, the scores range between -5 and 5, as in the previous case study. In Table 36 an example of scaling factor for EN1 is shown.

Table 36: Example of scaling factor of EN1 indicator

| **EN1** | | |
|---|---|---|
| **score scaling** | **min** | **max** |
| **-5** | -37.8 | |
| **-4** | -37.8 | -30.2 |
| **-3** | -30.2 | -22.7 |
| **-2** | -22.7 | -15.1 |
| **-1** | -15.1 | -7.6 |
| **0** | -7.6 | 0.0 |
| **1** | 0.0 | 8.5 |
| **2** | 8.5 | 17.1 |
| **3** | 17.1 | 25.6 |
| **4** | 25.6 | 34.1 |
| **5** | 34.1 | |

Time data for calculating the additional weight were taken from literature studies where similar interventions to the planned ones have been performed.

Data collected are shown in Table 37 along with the relative bibliographic sources.

Table 37: Estimated time for interventions

| Intervention | Time required | | Source |
|---|---|---|---|
| **D-E** | 2 | days | (9) |
| **A** | 15 | windows per day | (10) |
| **B-C** | 4 | days | (11) |
| **G** | 3 | hours | (12) |
| **H** | 1 | hour / room | (13) |
| **F** | 1 | hour / room | (14) |

Assumptions have been made for adjusting these data. As an example, in our case study air ducts for HVAC and pipes for DHW are already installed in the building and works properly. Accordingly, the original data about the installation timing were proportionally reduced. Regarding the costs, information was taken either from literature or from market price. Data, sources and relative scores are shown for each intervention in Tables 38 and 39.

Table 38: Time estimations scores

| Intervention | Hours | Score |
|---|---|---|
| **D-E** | 48 | 0.68 |
| **A** | 149 | 0.00 |
| **B-C** | 96 | 0.35 |
| **G** | 3 | 1.00 |
| **H** | 132 | 0.11 |
| **F** | 132 | 0.11 |
| **I** | 149 | 0.00 |
| **J** | 132 | 0.11 |
| **K** | 149 | 0.00 |
| **L** | 149 | 0.00 |
| **M** | 132 | 0.11 |
| **N** | 149 | 0.00 |

Table 39: Cost estimations scores

| | Cost (€) | Source | Score |
|---|---|---|---|
| **A** | 32865 | [15], [16] | 0.87 |
| **B** | 250337 | [15] | 0.00 |
| **C** | 74629 | [15] | 0.70 |
| **D** | 38400 | [17], [18] | 0.85 |
| **E** | 70900 | [18], [19] | 0.72 |
| **F** | 29645 | [20] | 0.88 |
| **G** | 4200 | [21], [22] | 1.00 |
| **H** | 8715 | [23], [24] | 0.97 |
| **I** | 107494 | Sum of COOL 2+Windows | 0.57 |
| **J** | 76760 | Sum of PV A+ EMS+Light | 0.69 |
| **K** | 184254 | Sum of T+E | 0.26 |
| **L** | 111694 | Sum of T+SHS | 0.55 |
| **M** | 80960 | Sum of E+SHS | 0.68 |
| **N** | 188454 | Sum of T+E+SHS | 0.25 |

In Table 40 is reported the final ranking. The best scenario is the combination of thermal, electric and the renovation of the Solar heating system (N) while the second position (K) is occupied by the thermal + electric scenario (PV, Management system and Lighting systems). The third position is occupied by the thermal + solar heating system (L). These three ranks show the importance of the thermal interventions combined with all the others. Regarding the single interventions, the best one is the improvement of the cooling system type B (C). The last positions are occupied by the refurbishment of the lighting system (H) and the Solar heating system (G).

Table 40: Final Ranking for Palazzo Baleani applying the QIMM method

| | **QIMM** | |
|---|---|---|
| **Ranking** | **Actions** | **Score** |
| **1** | N | 39.25 |
| **2** | K | 34.26 |
| **3** | L | 23.55 |
| **4** | C | 23.06 |
| **5** | I | 16.57 |
| **6** | B | 16.35 |
| **7** | A | 14.87 |
| **8** | J | -9.19 |
| **9** | M | -9.21 |
| **10** | E | -18.61 |
| **11** | D | -21.48 |
| **12** | F | -29.01 |
| **13** | H | -29.92 |
| **14** | G | -41.02 |

### 2.6.4 Palazzo Baleani case study: the Hybrid AHP method application

Finally, the application of the Hybrid AHP method to Palazzo Baleani, following the same procedure explained for the Sicilian residential district, was done. In this case, the weights of the ambits (2nd level) are 0.33 for Energy, 0.50 for Environment, 0.50 for Economy, 0.50 for Community. Moreover, due to the absence of stakeholders' opinion of the Palazzo Baleani case, the scores are given as if all the stakeholders hadn't voted.

Also in this application, the correction factor was added, according to the indicator's interpretation exposed in the previous paragraph. The steps of Hybrid AHP method, applied to Palazzo Baleani, are shown in Table 41 for Action A.

Table 40: Example of Local-global final table of each actions.

| | **Action A** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Indicators** | **Eigenvalues** | **Stakeholders preferences %** | **Evaluation Ambits** | **Goal level** | | **Final score** | |
| | **L4** | **L3** | **L2** | **L1** | **Sum** | **CF** | **G** |
| **EN1** | 0.0444 | 1 | 0.33 | 1 | 0.014652 | -1 | 0.05078 |
| **EN2** | 0.0376 | 1 | 0.33 | | 0.012408 | -1 | |
| **EN3** | 0.053 | 1 | 0.33 | | 0.01749 | 1 | |
| **ENV1** | 0.0769 | 1 | 0.5 | 1 | 0.03845 | -1 | |
| **ENV2** | 0 | 1 | 0.5 | | 0 | 1 | |
| **EC1** | 0.0148 | 1 | 0.5 | 1 | 0.0074 | -1 | |
| **EC2** | 0.0878 | 1 | 0.5 | | 0.0439 | -1 | |
| **Com1** | 0.1695 | 1 | 0.5 | 1 | 0.08475 | 1 | |
| **Com2** | 0.1307 | 1 | 0.5 | | 0.06535 | 1 | |

The pairwise comparison among the interventions is performed using the same procedure as in the previous case study. In Table 41 there is an example of EN1 matrix while in Table 42 the Eigenvectors calculation is shown.

Table 41: Example of Ratio matrix of each indicators

| | **Windows** | **COOL 1** | **COOL 2** | **PV A** | **PV B** | **EMS** | **DWH** | **Light** | **T** | **E** | **T-E** | **T-D** | **E-D** | **T-E-D** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EN1 | 1 | 0.803 | 0.838 | 0.495 | 0.504 | 0.480 | 0.464 | 0.477 | 0.635 | 0.564 | 0.904 | 0.674 | 0.569 | 0.966 |
| | 1.245 | 1 | 1.043 | 0.616 | 0.628 | 0.598 | 0.577 | 0.594 | 0.791 | 0.702 | 1.125 | 0.839 | 0.709 | 1.202 |
| | 1.193 | 0.959 | 1 | 0.590 | 0.602 | 0.573 | 0.553 | 0.569 | 0.758 | 0.672 | 1.078 | 0.804 | 0.679 | 1.152 |
| | 2.021 | 1.623 | 1.694 | 1 | 1.019 | 0.970 | 0.937 | 0.964 | 1.284 | 1.139 | 1.826 | 1.362 | 1.151 | 1.952 |
| | 1.983 | 1.593 | 1.662 | 0.981 | 1 | 0.952 | 0.920 | 0.946 | 1.260 | 1.118 | 1.791 | 1.337 | 1.129 | 1.915 |
| | 2.083 | 1.674 | 1.746 | 1.031 | 1.050 | 1 | 0.966 | 0.994 | 1.323 | 1.174 | 1.882 | 1.404 | 1.186 | 2.012 |
| | 2.156 | 1.732 | 1.807 | 1.067 | 1.087 | 1.035 | 1 | 1.028 | 1.370 | 1.215 | 1.948 | 1.454 | 1.228 | 2.083 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | 2.096 | 1.684 | 1.757 | 1.038 | 1.057 | 1.007 | 0.972 | 1 | 1.332 | 1.182 | 1.894 | 1.413 | 1.194 | 2.025 |
|  | 1.574 | 1.265 | 1.319 | 0.779 | 0.794 | 0.756 | 0.730 | 0.751 | 1 | 0.887 | 1.422 | 1.061 | 0.896 | 1.520 |
|  | 1.774 | 1.425 | 1.487 | 0.878 | 0.895 | 0.852 | 0.823 | 0.846 | 1.127 | 1 | 1.603 | 1.196 | 1.010 | 1.714 |
|  | 1.107 | 0.889 | 0.928 | 0.548 | 0.558 | 0.531 | 0.513 | 0.528 | 0.703 | 0.624 | 1 | 0.746 | 0.630 | 1.069 |
|  | 1.483 | 1.192 | 1.243 | 0.734 | 0.748 | 0.712 | 0.688 | 0.707 | 0.942 | 0.836 | 1.340 | 1 | 0.845 | 1.433 |
|  | 1.756 | 1.411 | 1.472 | 0.869 | 0.886 | 0.843 | 0.814 | 0.838 | 1.116 | 0.990 | 1.587 | 1.184 | 1 | 1.696 |
|  | 1.035 | 0.832 | 0.868 | 0.512 | 0.522 | 0.497 | 0.480 | 0.494 | 0.658 | 0.583 | 0.935 | 0.698 | 0.590 | 1 |

Table 42: Example of eigenvectors calculation as local values.

| Indicator | Eigenvectors |  | Eigenvectors (divided by the Sum) | Actions |
|---|---|---|---|---|
| EN1 | **v1** | 0.644 | 0.0444 | **A** |
|  | **v2** | 0.802 | 0.0553 | **B** |
|  | **v3** | 0.769 | 0.0530 | **C** |
|  | **v4** | 1.302 | 0.0898 | **D** |
|  | **v5** | 1.278 | 0.0881 | **E** |
|  | **v6** | 1.342 | 0.0925 | **F** |
|  | **v7** | 1.390 | 0.0958 | **G** |
|  | **v8** | 1.351 | 0.0932 | **H** |
|  | **v9** | 1.014 | 0.0699 | **I** |
|  | **v10** | 1.143 | 0.0788 | **J** |
|  | **v11** | 0.713 | 0.0492 | **K** |
|  | **v12** | 0.956 | 0.0659 | **L** |
|  | **v13** | 1.1320 | 0.0780 | **M** |
|  | **v14** | 0.6674 | 0.0460 | **N** |
|  | **Sum** | 14.5093 |  |  |

The final results are provided in Table 43.

Table 43: Final ranking for Palazzo Baleani case study applying the Hybrid AHP method

| | **Hybrid AHP** | |
|---|---|---|
| **Ranking** | **Actions** | **score** |
| **1** | **N** | 0.22 |
| **2** | **K** | 0.20 |
| **3** | **L** | 0.16 |
| **4** | **C** | 0.15 |
| **5** | **B** | 0.14 |
| **6** | **I** | 0.12 |
| **7** | **A** | 0.05 |
| **8** | **J** | -0.08 |
| **9** | **M** | -0.09 |
| **10** | **E** | -0.13 |
| **11** | **D** | -0.14 |
| **12** | **F** | -0.20 |
| **13** | **H** | -0.21 |
| **14** | **G** | -0.53 |

The ranking highlights that the best scenario is the combination of thermal + electric + the renovation of the Solar heating system scenario (N) followed by the thermal + electric scenario (K) and the thermal + solar heating system (L). Regarding the single interventions, the best one is the improvement of the cooling system type B (C), which concerns the installation of an air handling unit and an inverter heat pump. The replacement of lighting fixtures (H) and solar heating system (G) got, instead, the lowest score. It is worthy to notice that the four best and the two worst interventions are the same in the two methods.

## 2.7 Discussion

### 2.7.1 Sicilian residential district case

Comparison between the final rankings of the Sicilian residential district, obtained through the application of QIMM and Hybrid AHP methods, is shown in this section.

Table 44: Final rankings of the Sicilian residential district with both methods

| Ranking | Hybrid AHP | QIMM | Changes in QIMM respect to AHP |
|---|---|---|---|
| **1** | D | D | = |
| **2** | J | E | ↑ 1 |
| **3** | E | C | ↑ 1 |
| **4** | C | I | ↑ 1 |
| **5** | I | J | ↓3 |
| **6** | B | A | ↑ 1 |
| **7** | A | F | ↑ 2 |
| **8** | K | B | ↓2 |
| **9** | F | K | ↓1 |
| **10** | H | H | = |

The comparison of Table 44 shows that the first and last positions of the ranks are aligned. The other positions are quite similar apart from a few differences. The main variation regards intervention J. Action J (Solar thermal collectors) occupies the second position in the Hybrid AHP and only the fifth in QIMM. Analysing more in detail the results of this action in Table 19, it can be noticed that indicators have overall very good values, especially EN1, EN3 and ENV1.

However, its final score in QIMM, was considerably reduced after the normalization process due to the scaling of few indicators, such as EN2. As an example in Table 45, the values of EN 2 for all the actions are shown. It can be seen that the values of the action are very similar to each other and the absolute differences are very low (the maximum difference is only 0.7 toe/M€ between actions I/A/C and J). Nevertheless, the type of normalization proposed in QIMM increases these differences on the 5 to -5 scale giving the highest score to actions I, A and C and the lowest possible to action J. This is one of the main characteristics of the QIMM method: even when the absolute differences among the indicator values are not considerable, the normalization process brings the value on a score scale (-5/+5) which increases the differences among the actions.

Table 45: Example of an Indicator values and scores

| **Indicators/ Actions** | | **A** | **B** | **C** | **D** | **E** | **F** | **H** | **I** | **J** | **K** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **EN2** | **Energy intensity of the residential sector (toe/M€)** | 26.4 | 26.10 | 26.40 | 26.10 | 26.30 | 26.30 | 26.30 | 26.40 | 25.70 | 26.10 |
| **Score of QIMM method** | **Energy intensity of the residential sector (toe/M€)** | **5** | **-1** | **5** | **-1** | **2** | **2** | **2** | **5** | **-5** | **-1** |

The intention is therefore to assess if this peculiarity of the QIMM method in the scaling process could have caused the differences in the two ranks, especially regarding action J. Accordingly, authors decided to develop an additional analysis. The vote of the stakeholders and the weight of indicators (Level 2) in the Hybrid AHP and the cost and time scores in the QIMM method were therefore excluded, in order to compare only the results of the two normalization processes (Table 46).

Table 46: Final rankings of the Sicilian residential district (without weights and additional scores)

| **Methods without weights and additional scores** | | | |
|---|---|---|---|
| **Ranking** | **Hybrid AHP** | **QIMM** | **Changes in QIMM respect to AHP** |
| **1** | D | D | = |
| **2** | E | E | = |
| **3** | C | C | = |
| **4** | I | I | = |
| **5** | A | J | ↑ **1** |
| **6** | J-F | A | ↓**1** |
| **7** | B | F | ↓**1** |
| **8** | K | B | ↓**1** |

|  |  |  |  |
|---|---|---|---|
| **9** | H | K | **↓1** |
| **10** | - | H | **↓1** |

Results in Table 46 show that if additional scores in the two methods are not considered, the two ranks are much more similar to each other. The absence of the stakeholders in the Hybrid AHP method has, therefore, an impact in the evaluation of actions J, F and B, which got in Table 46 about the same positions occupied in the QIMM rank (Table 46). Referring for example to action J, it can be seen that in Table 44, it occupied the 2nd position while in Table 46 it is placed at the 6th. Conversely in QIMM, the absence of cost and time scores doesn't affect the rank, since these weights only intervene at the end of the scoring process; comparing Table 44 and 46 for the QIMM method, the rankings are exactly the same. It demonstrates that the economic and time scores in the QIMM approach have a lower impact compared to the stakeholders' vote used in the AHP method. The inclusion of these two factors can indeed mainly help in diversifying the scores if two actions occupy the same position in the rank after the normalization process.

As shown in Tables 44 and 46, in the Hybrid AHP method the impact of the stakeholders has a role on the rank, making a few actions increase or decrease their positions in the ranks. This fact highlights the role of the stakeholders in the process: if high relevance is given to their opinion a kind of subjectivity is included in the model, but from the other side, if less power is given to their votes, their potentiality in the decision-making process is reduced.

### 2.7.2 Palazzo Baleani case study

Comparison between final rankings of the Palazzo Baleani, obtained through the application of QIMM and Hybrid AHP methods, are shown in this section. Results are shown in Table 47.

Table 47: Final rankings of Palazzo Baleani with both methods

| **Ranking** | **Hybrid AHP** | **QIMM** | **Changes in QIMM respect to AHP** |
|---|---|---|---|
| **1** | N | N | = |
| **2** | K | K | = |

| | | | |
|---|---|---|---|
| **3** | L | L | = |
| **4** | C | C | = |
| **5** | B | I | ↑ 1 |
| **6** | I | B | ↓1 |
| **7** | A | A | = |
| **8** | J | J | = |
| **9** | M | M | = |
| **10** | E | E | = |
| **11** | D | D | = |
| **12** | F | F | = |
| **13** | H | H | = |
| **14** | G | G | = |

In Table 47, the two rankings are very aligned. Differently from the Sicilian district, the stakeholders votes are not provided at the beginning of the process. Consequently, the absence of this factor in the Hybrid AHP method allow to make the two ranks more similar compared to the other case study (Table 46). This consideration highlights again that the normalization process of the two methods are comparable.

Knowing that for this case study the stakeholders' opinion is not considered, the ranks without including the weights of the ambits (in the Hybrid AHP method) and the cost and time scores (in the QIMM) are shown in Table 48.

Table 48: Final rankings of Palazzo Baleani (without weights and additional scores)

| **Methods without weights and additional scores** | | | |
|---|---|---|---|
| **Ranking** | **Hybrid AHP** | **QIMM** | **Changes in QIMM respect to AHP** |
| **1** | N | N | = |
| **2** | K | K | = |
| **3** | L | L | = |
| **4** | C | C | = |

| | | | |
|---|---|---|---|
| **5** | B | B-I | ↑**1** |
| **6** | I | A | ↑**1** |
| **7** | A | J-M | ↑**1** |
| **8** | J-M | E | ↑**1** |
| **9** | E | D | ↑**1** |
| **10** | D | F | ↑**1** |
| **11** | F | H | ↑**1** |
| **12** | H | G | ↑**1** |
| **13** | G | - | **-** |
| **14** | - | - | **-** |

As expected, since the original rankings were yet very aligned, the scores did not change much compared to Table 47. Nevertheless, a few actions got an equal position in the rank, especially with the QIMM (actions B and I; actions J and M): it underlines again that the main role of the cost and time scores is to differentiate the final performance of the interventions, removing the equal positions as shown in Table 47.

Summing up the general considerations about the two methods:

1- The normalization processes of the two methods provided aligned and comparable results.
2- The opinion of the stakeholders in the Hybrid AHP method has a higher impact in the final rank than the cost and time scores in the QIMM.

Specific observations regarding the QIMM coming out from the results, are the following:

1. The inclusion of the correction factor in the scoring process is a strong point of the methodology since it allows to give a correct interpretation of the indicators analysing their significance in respect to the others. This aspect was missing in the original Hybrid AHP method but, in this work, it was added in the formula for the comparison between the methods.
2. The application of the normalization process is easier compared to the Hybrid AHP.
3. The cost and time scores in the QIMM method allow to remove the equal positions in the ranks.

## 2.8 Conclusions

The current work aims to describe and validate the QIMM planning approach through the comparison with the Hybrid AHP method and the application of these two models to two real case studies. These two MADM approaches were chosen since they allow to identify which are the best solutions from an integrated perspective, taking into account as much as possible the impacts of the strategies on different Smart fields. The proposed model has been originally elaborated by the authors in [11, 72] and it was modified in the current work, transforming it into a quantitative ex-post approach. The evolution of the method from qualitative to quantitative meets the needs evidenced in literature in the development of Smart City projects: quantitative and holistic planning models are required to identify objectively the problems of the cities and to identify the most efficient strategies in a set of multiple possible scenarios. The comparative Hybrid AHP model has been indeed developed in previous literature work by [80].

The real case studies belong to two different territorial levels: a district and a building. This choice was made to demonstrate the flexibility of the two approaches. The comparison between the methods allowed: to assess the impact of the different methods on the prioritization process for a set of Smart actions; to underline similarities, differences, lacks and strengths of the two models.

In general, results show that the two approaches, despite their differences, give the same outputs regarding the best and worst-performing solutions. In both case studies the first and last positions in the ranks are the same with the two models.

Regarding the Sicilian case study, stakeholders' opinion included in the Hybrid AHP method has a relevant impact on the score of a few actions, considerably altering their positions in the rank. Accordingly, the ranks of the two methods are not completely aligned with regard to the intermediate positions. Nevertheless when the stakeholders' opinion of the Hybrid AHP and the additional cost and time scores in the QIMM are excluded from the analysis, the ranks come out to be very similar. It demonstrates that that the normalization process of the two methods give comparable results despite their considerable differences.

The Baleani case study shows instead aligned results with the two methods, mainly because the stakeholders' vote is not included.

Summing up, the stakeholders opinion in the Hybrid AHP method has a higher impact on the final rank compared to the economic and time feasibility scores used in the QIMM: when stakeholders' votes are not considered, the rank obtained with the Hybrid AHP method equalizes with the rank produced with the QIMM model.

Results, therefore, demonstrated the reliability of the normalization process used in QIMM and allowed to pinpoint the following positive aspects of the method:

- Easiness of normalization process
- Unbiased attribution of the scores in the scaling process
- The objectivity of the prioritization process by applying quantitative parameters: correction factor and economic and time weights
- Replicability of the method and applicability to different territorial scales

Limits of the methods are also evidenced. The stakeholders' opinion in the Hybrid AHP model has a clear impact on the final ranking; it demonstrates that high importance is given to the users which, on the other hand, could make the results too subjective. Regarding the QIMM, its additional scores have a lower influence on the final results compared to the relevance of the normalization process. Their role is mainly to differentiate the scores of two actions when they occupy the same position in the rank. The absence of the stakeholders' votes in QIMM allows indeed to make the entire process more objective, but on the other side, it would be useful to take their opinion into account.

# Chapter 3

# SMART METHODOLOGY (QIMM): APPLICATION TO A RESILIENT ENERGY MICROGRID

## 3.1 Introduction

Today, the thermal and cooling energy demand of the building sector is attested around 40% of the total European energy consumption, giving an evident impact on the carbon emission level [88]. Several European directives established limits and sustainable targets due to climate change and global warming [89]. Considered as a promising green alternative solution able to face with the current energy and environmental forceful call, the District Heat Networks (DHN) has been developed throughout recent years [90, 91]. Furthermore, the use of renewable energy sources (RES) and the decreased need of fossil fuel are both the main advantages of this technology, as discussed in the reported literature [92]. In numbers, about 11-12% of the total Europe heat demand in 2017 was supplied by the DHN, as the Euroheat & Power report [93] underlined.

Regarding the energy generators systems that feed the DH plants, they are various in literature, such as fossil fuel, biomass or MSW from waste-to-energy), cogeneration plants, heat pump systems (which use renewable hydrothermal, geothermal renewable energy) or solar thermal. It has to point out that thanks to the technology progress the actual energy generator system is moving to a new intergrade scheme, becoming a multiple source system [94]. Among this, the use of CHP plants, especially in Europe, achieved the best position in terms of energy generators for DH systems [94] providing about 56% of the heat supply as exposed in [95]. Moreover, reducing the CO2 emission and primary energy need are two attractive qualities of the CHP plant, as suggested in [96].

According to the “World energy Balances: Overview” by the International Energy Agency (IEA)”, biomass (materials and residues of agricultural and forestry origin, secondary products and waste from the agri-food industry, livestock waste and urban waste) was the first source of energy used by humans, and it is still one of the most widespread. Due to being a green alternative to fossil fuels (wood chip—0.015 kg CO2e/kWh compared to 0.204 kg CO2e/kWh natural gas), it is used for feeding several energy system, such as CHP/DH, providing thermal energy to a wider range of stakeholders [94, 97].

During the last years, the resilience concept has been defined and adapted to a wide range of fields [98, 99, 100]. This theme was developed in psychology and physics as a measure of stability that shows the ability of an object to survive a specific trauma and to maintain the original equilibrium. Then, many studied have been applied this concept to other disciplines such as ecology and urban contexts [101, 102]. Moreover, today the concept of cultural heritage resilience begins an important issue able to face with the natural phenomena (e.g. heart quake). In line with this, urban resilience became a complex box containing several meanings, from the ecological aspect to the energy system. Regarding this one, the engineering resilience described the ability of an energy system to overcome risks, enhancing its resistance and robustness [103].

## 3.2 State of art

### Resilience energy system

A detailed review of [103] highlighted clearly principles and criteria useful for the urban energy resilience assessment. Among this, this research analyses 196 works and they draft a list related to the characteristics of a resilient urban energy system: robustness, stability, flexibility, resourcefulness, redundancy, diversity, foresight capacity, independence, interdependence, collaborator, agility, adaptability, efficiency.

The authors underline that only four of them obtained an important role, such as redundancy, diversity, adaptability and efficiency. Moreover, it was possible to identify five themes related to the resilient urban energy, such as infrastructures, resource, land use, governance and human behaviour. Those five categories are useful for better identifying resilient criteria inside each of them, to develop an urban resilience settlement.

### District Heating Network (DHN)

In literature, several works caught the opportunities to implemented and improved the DHN system [104], analysing different aspects, related to the distribution configuration, the control devices, and thermal storage. Among the distribution field [105, 106], some researchers were focused on the thermal losses piping [105] proposing different pipe configurations able to minimize the losses. Others [106], started from the pipe materials, pressure losses, and installation plant analysis, defined an optimal design for the geothermal DH. The piping optimization achieved a huge interest in the works of [107, 108] as a result of a fast modelling approach that could choose and adapt the optimal piping size to the load changing. On another hand, the works of [109, 110] investigated different optimal configurations to face several failure events, avoiding discomfort to the end-users due to pipe ruptures and adjusting the thermal energy demand in case of a blackout, respectively. Another tendency, discussed in [111], highlights the possibility of monitoring several units (e.g. temperature, pressure, mass flow), allowing technicians to control the operational failures and to evaluate the energy performance by the use of data-driven models. Finally, according to ([112], the role of the thermal storage in the DH system is often under development due to its importance in terms of facing the daily varying energy demand.

### Cooling and Heating Power system (CHP)

A comprehensive review elaborated by [113] underlines the interest of various experts in the DH/CHP application, highlighting that most technologies of power generation in CHP systems are steam turbines, gas turbines and combined gas-steam turbines (GTCC-gas turbine combined cycle). From the economic view, the work of [96] proposed an evaluation methodology for the analysis of the CHP/DH implementation at a regional level, as a tool for enhancing energy polices. Tanks to the Danish experience, the work of [114] presents the new methodologies and tools, which have been used to design investment and operation strategies for the optimization of small CHP plant designs, during the decade of the triple tariff. Another tool used to identify potential scenarios and the cost of expanding district heating is the Geographical Information System (GIS), as reported in [115]. In this research, different combinations for residential heating technologies displacement in Denmark were analyzed. The work of [116], instead, demonstrated how and what type of composite indicators can optimize the operative strategy of the CHP, facilitating the plant performances and design assessment. Finally, a further development of the DH/CHP, located in Turin Italy, is proposed by [117], carrying on this strategy with environmental compatibility in terms of the local impact of NOx and PM.

**Biomass renewable energy source (woodchip)**

Among the biomass type, the woodchip one is particularly interesting due to the low energy requirements for its production and with very stable burning compared to other solid biofuels [118]. Indeed, they investigated the quality of woodchip, through an evaluation of the most important chemical and physical parameters, demonstrating its goodness even the presence of high ash content. Another aspect that achieved interest is the correct biomass CHP plant sizing respect to the building energy demand, being more difficult to evaluate compared to the industrial sector request. In line with this, the work of [119] presents a useful methodology, applied to the University campus in Liège (Belgium), to assess the average conversion efficiencies over a complete year of operation and to provide reliable estimates for energy cost forecast. Another work of [120] proposed a pilot project about a district heating system powered by a biomass CHP plant in Perugia (Italy). This project is developed with the Governance accordance, who want to enhance an independent energy system for rural villages, whose economy is based on agricultural activities.

This brief overview on the DH/CHP system highlights its spread through the European countries. On the other hand, the use of woodchip as primary source for feeding the CHP is still under development but presents exceptional potentiality in term of local exploitation and economic incentives [119,121]. Furthermore, the DH network allows to enhance hybrid substations and promote sector coupling between electrical and thermal grids in a smart energy system [122].

More than one DH network connected, feeding by biomass CHP plant, becoming a concrete energy microgrid, in which thermal and electrical energy is supplied to the end-users. Regarding the microgrid, it had been deeply investigated during the last twenty years, as discussed [123], in which the strengths and weaknesses of its application are pointed out. Indeed, several researchers underlined the powerful role of the microgrid for enhancing the resilience for a district, as reported in the work of [124]. Authors developed a microgrid with an electrochemical energy storage system, demonstrating how this system can increase the power resilience, thanks to the inclusion of renewable sources (photovoltaic solar energy).
Indeed, the DH technology represents a high potential because of its resilience, exploitation of indigenous renewable sources and the interconnection with the electric grid and CHP units that could shift from electricity to heat generation and vice-versa [125, 104]. Even though different works mentioned above recognized the potential of energy microgrid, few of them apply this system into a real case study, to quantify the relative benefits and advantages. This is mainly due to the lack of practitioners required for the microgrid design, as well as the gap in the knowledge of the technical challenges encountered during the CHP sizing and the distribution networks development.

To cover this gap, this work proposes an energy microgrid composed of CHP biomass plant (based on a steam turbine cycle) as the energy generator system and district heating networks as the distribution one, applied in mountain Italian communities. Six villages are connected through the DH networks, providing thermal and electrical energy thanks to the biomass CHP plants. The use of local sources as woodchip follows the main European calls for renewable sources integration into the energy generation system.

Additionally, different CHP plant sizing scenarios have been elaborated to ensure the resilience goal for those communities, faced with failures and blackout events. Although in literature, many works are facing with the energy resilient system [101, 102 ,103], few of them [126] concretely proposed indexes and measurements for developing it.

Thus, this work could significantly contribute to the pool existing application cases and provides a reference methodology considering especially mountain villages in the South of Italy. The energy system scheme was developed with the MATLAB/Simulink tool, analyzing in a dynamic way the main factors (e.g. flow distribution, temperature, energy performance), knowing the load profile throughout the year is far from being constant, especially for the residential users. However, other authors in literature attested the reliability of the MATLAB/Simulink simulations of a DH network, applied in the real town of Kiruna (Sweden) [127].

Moreover, a smart methodology is applied to this case study to understand which scenario represents the global smart solution for those Italian communities. A lot of variable playing a strong role in this work: the use of renewable source (purchased or self-product), the use of DHN with CHP, the design of different seize of this energy microgrid to guarantee the resilience of it. Therefore, the QIMM approach could give correct weights and scores to the smart strategy that most deal with the problems. In line with this, several smart indicators are elaborated aiming to describe the impact of that scenario in a global and holistic view. Resilient indices were defined, exploring the importance of the positive aspects of a resilient energy system and pointing out the weakness of a non-resilient one.

## 3.4 Aim and Methodology

The aims of this work, exposed in this chapter, is to:

- Develop an energy microgrid for the mountain Italian communities. This system is composed of CHP biomass plant and a District Heating Networks (DHN), using the woodchip as a local source.

- Propose resilient scenarios able to face with failure events. In details, two scenarios of resilient energy microgrid are defined and analysed.

- Apply the QIMM approach to the different energy system scenarios to highlight their potentialities and their weaknesses. Moreover, a set of resilient performance indicator was elaborated by the author allowing to point out their effectiveness on the final smart ranking.

The first step of this study is to develop the energy microgrid and the Simulink, a MATLAB tool, was chosen. A set of simulations were carried out, analyzing dynamically the main factors related to the building, the generation plants, the DHN and the entire microgrid (e.g. flow distribution, temperature, energy performance). In the following sections, the author described the case study, the energy generator system chosen, the use of local sources (woodchips), and the structure of the six DHN village's, included in the energy microgrid. Then, some paragraphs are dedicated to showing the methodology adopted for energy microgrid definition, starting from one village (Sersale) analysis. Thermal and electrical needs are calculated, following by the DHN and CHP biomass plant power sizing, implementing each aspect in Simulink. Other village's energy demands are developed basing on the Sersale case. Finally, other different scenarios will be presented to obtain a resilience energy microgrid.

To define the best energy configuration, the QIMM methodology is adopted. A set of smart and resilient indices were elaborated by the author. Following the phases of the QIMM method, it was possible to draft the smart ranking of those scenarios. Moreover, a resilient analysis was done, to understand the influence of the resilient smart indicators on the final smart rankings.

## 3.5 Description of the Case study

Six villages of the southern area of Sila Piccola Meridionale, located in the South of Italy, are included in the energy microgrid: Sersale, Cerva, Petronà, Andali, Zagarise and Maisano (Table 49). The major urban centre is Sersale with its 4605 inhabitants and it also represents the geographical centre of the network's energy distribution. The other villages are located radially to it, at a maximum distance of 8.6 km.

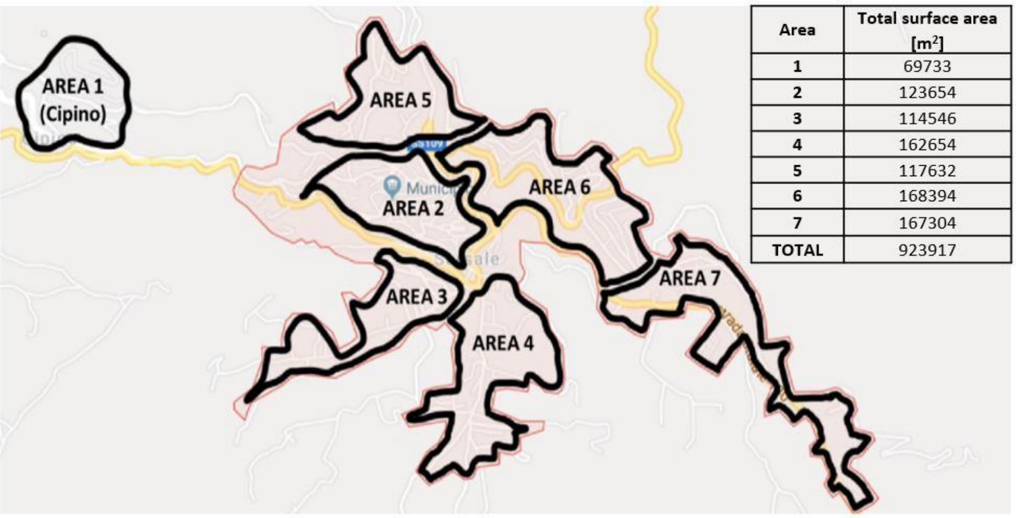
Table 49: Main information about the villages included in the energy micro-grid

| | Inhabitant | Surfac | Populatio | Altitud | Climatic | Distance from |
|---|---|---|---|---|---|---|

|  | s | e area | n density | e | zone | Sersale |
|---|---|---|---|---|---|---|
|  |  | [km$^2$] | [In./km$^2$] | [m] |  | [km] |
| Sersale | 4605 | 53.30 | 86.40 | 740 | E | 0 |
| Cerva | 1212 | 21.37 | 56.67 | 860 | E | 2 |
| Petronà | 2594 | 45.79 | 56.11 | 889 | E | 4.3 |
| Andali | 728 | 17.87 | 40.74 | 650 | E | 3.5 |
| Zagarise | 1628 | 49.33 | 33.39 | 581 | D | 5.6 |
| Magisano | 1230 | 31.94 | 37.63 | 565 | D | 8.6 |

As aforementioned in the introduction section, the presented work aims to develop an energy microgrid, to cover the thermal and electrical energy needs for those six mountain villages. Moreover, the other two resilient scenarios are elaborated to guarantee the energy requirements for the users in case of failures or blackout of the networks. Then, several simulations are carried out, starting from the village's energy needs to the energy power CHP biomass plant assessment. The six DHNs connected are deeply investigated thanks to the Simulink potentialities, as the authors highlight in the following paragraphs.

The first step is to simulate both the thermal and electrical requirements of those villages, starting from Sersale. Due to its largest dimension compared to the other communities, Sersale is chosen as a reference simulation model. The definition of the other villager's energy needs indeed will be based on the results obtained for Sersale. It is possible to divide the buildings of the Sersale into seven blocks, or macro-areas, (Figure 16) which may be built-up in the same historical period [128].



| Area | Total surface area [m$^2$] |
|---|---|
| 1 | 69733 |
| 2 | 123654 |
| 3 | 114546 |
| 4 | 162654 |
| 5 | 117632 |
| 6 | 168394 |
| 7 | 167304 |
| TOTAL | 923917 |

Figure 16: Seven macro-areas of Sersale buildings

Once the macro-areas have been identified, the authors used an approximated method [129], the plot ratio method [130], for quantifying the total amount of building distributed in each selected zone. Another useful information is the number of families living in the village, attested to 1681unit with an average of 2.89 components. In line with this, the thermal and electric energy needs calculation will consider each residential building to be occupied by a single family of 3 people. The structures for non-residential uses are arbitrarily distinguished into commercial (60% of the non-residential buildings) and office ones (40% of the non-residential buildings). Therefore, three categories of buildings (residential buildings, commercial buildings, offices) and three different stratigraphy's are identified (Table 50). In numbers, the total amount of residential buildings are 2005, 110 for commercial use, and 74 for offices.

Table 50: Geometrical characteristics of three different typologies of users

| | | Residential building | Commercial building | Office building |
|---|---|---|---|---|
| Height | [m] | 6 | 4 | 9 |
| Length | [m] | 10 | 10 | 10 |
| Width | [m] | 5 | 10 | 8 |
| Nr of floors | - | 2 | 1 | 3 |
| Total useful surface | [m$^2$] | 100 | 100 | 240 |
| Volume | [m$^3$] | 300 | 400 | 720 |

### 3.5.1 Energy generation system

The wood biomass availability in the case study area, the Sila Piccola Meridionale, suggests the installation of a CHP biomass plant-based on a steam turbine cycle, operated according to a back-pressure configuration. The choice for the back-pressure steam turbine arrangement derives from technical considerations [119].

Moreover, the combination of internal combustion engines and gas turbines are suitable technological scheme for small and medium CHP (power lower than 2 MW, as this case study). This technical system is generally operated with the bypass of steam at the exit of the turbine rather than with steam extraction. Furthermore, the low electric efficiency of a back-pressure steam cogeneration plant, which represents its main drawback, is justified in this work by the high required thermal load of those mountain villages. The low value of the cogeneration ratio, characterizing this type of plant, indeed does not represent an issue for a DHN application.

### 3.5.2 Calculation of the energy requirements

Simulink software was used to calculate the total energy demand. To obtain results as close as possible to real consumptions, some parameters such as occupancy, ventilation rate, internal heat gains were estimated with the tool.

To define the thermal and cooling energy needs requirements, weather conditions of the building location must be taken into account. In this study, the "Neural weather generator", a climate condition simulator developed by Enea [129], was used, which is based on the techniques of Soft-computing [131]. This model allows to obtain data about temperature, humidity, and solar radiation. The result of the environmental temperature trend over the year (8760 hours), used for the Simulink simulations, is shown in Figure 17.

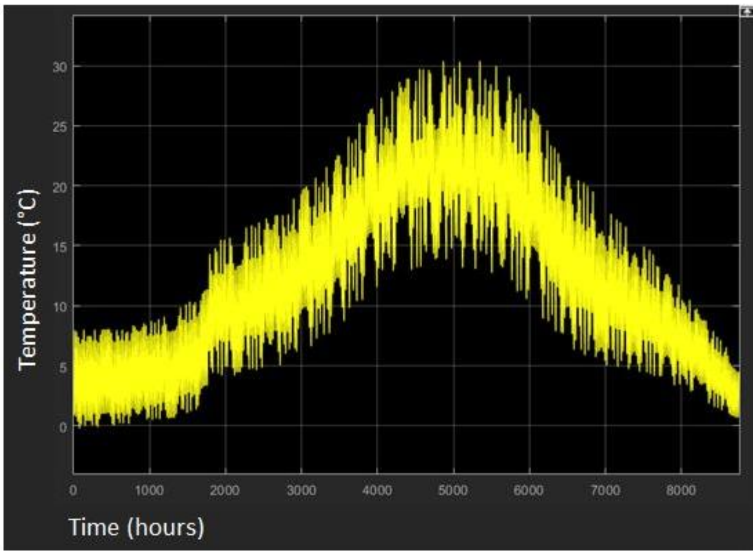


Figure 17: Environmental temperature trend during the year [°C]

Sersale, as expected, is not a severe hot location since the maximum temperature reached during the summer is about 30 °C, while during the winter it can drop up to 0 °C. The model also provides a daily temperature trend. Following, the hourly distribution of thermal and electric loads and internal gains are described briefly below.

<u>Presence of people.</u> As aforementioned, the residential buildings are occupied by a single family of 3 people. During the evenings and nights of ordinary days, indeed, a maximum of three occupants are considered in the building; on the other hand, during the day, only a single person is estimated. Regarding the non-residential buildings, the average occupancy is established in line with the standard UNI 10339 [132]. This average value is equal to 17 for commercial buildings and 13 for offices. For commercial buildings, supposed as a department store of 100 m$^2$, the working hours could be estimated from 9 am to 8 pm, from Monday to Saturday; conversely, from 9 am to 1 pm on Sunday. The total number of employers are set to 6, the cleaners to 2 and the costumers to 30. Finally, the office buildings are organized on three floors of 80 m$^2$ each: 70 % of the total useful surface is effectively occupied, while 30 % is constituted by corridors and other common areas. A total number of 17 employers are estimated, assuming a 10 m$^2$ available for each of them. In this case, the working hours are 8 am to 1 pm, 2 pm to 5 pm from Monday to Friday and 8 am to 1 pm on Saturday.

<u>Ventilation rate.</u> To ensure an external air inlet value, the UNI 10339 standard [132] was used. The calculation of the air renewals needed is shown in Table 51.

Table 51: Calculation of air renewals needed in the different types of buildings according to [132]

| Type of building | Useful surface | Volume | Crowding index | N° of people | Flow rate of external air | Flow rate of external air | Air renewal |
|---|---|---|---|---|---|---|---|
| | [m$^2$] | [m$^3$] | [people/m$^2$] | - | [m$^3$/(h*person)] | [m$^3$/h] | [1/h] |
| Residential | 100 | 300 | 0.04 | 4 | 39.6 | 158 | 0.5 |
| Commercial | 100 | 400 | 0.25 | 25 | 32.4 | 810 | 2.0 |
| Offices | 240 | 720 | 0.06 | 14 | 39.6 | 570 | 0.8 |

The values reported for the "Air renewal" column in Table 3 are used during the hours in which the building is occupied or the plant is on. On the other hand, when the plant is off the values assumed for the air renewal are 0.2 for residential buildings and 0.1 for non-residential ones, taking into account the infiltration through the building envelope.

*Internal heat gains*. The people occupancy, the lighting systems, and other electric devices contribute to increasing the internal temperature of a buildings, due to their heat emissions, as well as the solar radiation. The Standard UNI/TS 11300-1 [133] provides therefore the values of the global thermal internal loads (due to the people occupancy and electric devices) per unit of a floor, (i.e. in $W/m^2$), for different structures uses. These values are set for weekdays and weekend ones, providing an hourly basis for residential and office buildings; while the hourly profile of the internal gains for commercial buildings can be determined from standards [133].

*Electric load curves*. The electric energy requirements are calculated in the simulation model based on the electric load curves. The building electric power needs of a typical day presents two peaks, one at 1 pm and another at 9 pm, following the maximum electric demand.
Regarding the commercial buildings, the electric load profile during a working day is in line with "Electric load patterns for residential, commercial, industrial usage" [134]. To obtain the real curve, the value of the installed electric power capacity was estimated equal to 6 kW. For the offices, the electric load curve is equal to 4.5 kW, knowing the electrical system power installed in the store. Finally, it was assumed that the electrical energy consumption of non-residential buildings slightly decreases during lunchtime.

*Domestic Hot Water requirements*. To calculated the thermal energy needed for the Domestic Hot Water (DHW), the flow rates of water required and its temperature (inlet and outlet) were elaborated based on technical data. The thermal power $P_{th\ DHW}$ indeed is given by the formula below:

$$P_{th\,DHW} = \varrho \cdot \dot{V} \cdot c_{p,W} \cdot (T_{W\,out} - T_{W\,in})$$

Equation 15.

where: $\varrho$ is the water density equal to 1000 $kg/m^3$; $\dot{V}$ is the required volumetric flow rate of water in terms of $m^3/s$; $c_{p,w}$ is the specific heat of water, equal to

4.186 kJ/(kg·K); $T_{w\ out}$ and $T_{w\ in}$ are respectively the temperature at which the water must be heated and the cold water intake temperature, assumed equal to 40 °C and 15 °C, according to the Standard [134]

In the residential building case, the hourly trend of the water volume required during a day by the occupants was chosen from the UNI-EN/16247 [135] guidelines. For the non-residential use, the daily values are provided by the Standard UNI EN 11300-2 [134]. For both commercial buildings and offices, the daily required volume of DHW is equal to 0.2 l/(day·m$^2$).

## THE MODELS OF CHP BIOMASS PLANT AND THE DHN

### The DHN plant

In this paragraph, the DHN and the CHP biomass plant, modeled in Simulink, are simulated for the Sersale case. The inputs of the District heat networks are reported below:

- The values of the mains water mass flow rates delivered to the macro-areas of the village (kg/s);
- Temperatures of the network water stream at the exit of each block of costumers (°C);
- The total electric and thermal power requirements of the macro-areas of Sersale (kW);

These parameters play an essential role in the simulations, with the aim to evaluate:

- The total mass flow rate (kg/s) of mains water which is extracted from the network accumulator in order to feed the buildings, equal to the sum of the flow rates fore-calculated;
- The temperature at which network water reaches the nodes of delivery to the different macro areas (°C);
- The temperature of the fluid which comes back to the hot tank through the return network (°C);
- The total heat losses occurring along with the delivery network and along with the return network as well as their sum (kW);
- The network efficiency;
- The total electric and thermal power requirements of Sersale's buildings, connected to the DHN system (kW);

- The thermal power extracted from the network accumulator during the operation of the system to meet the customer's demand (Q load, network accumulator, kW).

Using two Matlab functions that estimate the temperature difference between mains water and the soil which surrounds the insulated pipes of the DHN plant, the heat losses are calculated, according to the formula below:

$$Pth_{loss} = G \cdot c_{p,W} \cdot \Delta T$$

Equation 16.

Where G is the mass flow rate of water flowing through the pipe of the DHN (kg/s), $c_{p,W}$ is the water-specific heat (kJ/(kg·K)) and ΔT is the difference between the water temperatures at two different consecutive nodes (°C) at the extremes of the pipe. A Simulink block calculates the of network water required by the individual user. This block assumed the mass flow rate constant during the network operation; while the water temperatures, in correspondence of specific nodes of the DHN, will change over time.

Finally, the thermal level of mains water located in each node of the delivery network is calculated with the expression:

$$T(x,t) = T_{soil} + (T_{node} - T_{soil})e^{\frac{-2 \cdot \pi \cdot H}{G \cdot c_{p,w}}x}$$

Equation 17.

where: $T_{soil}$ is the soil temperature equal to 15 °C; $T_{node}$ is the temperature of the node that forerun the one for which the temperature ha to be calculated (°C); H is the pipe transmittance (kW/(m·K)); x is the length of the concerned pipe in meters, (i.e. the distance between the two considered nodes).

In correspondence of the return network nodes the water reaches an average thermal level of the water temperatures mixing in that point, weighted with their mass flow rates:

$$T_{node} = \frac{\sum_i T_i \cdot G_i}{\sum_i G_i}$$

Equation 18.

The heat losses assessment is defined for both the delivery and return networks. The aforementioned evaluation of thermal losses ensured the over-zing of the generation system but also guaranteed an adequate temperature value of the heat transfer fluid when this reaches the thermal needs of the users. The sizing of the pipes of the DHN is a crucial point to deal with, and therefore, it could be necessary to place it along a rather wide road.

The simulated network has an indirect branched configuration, which ensures economic convenience during the realization phase or the future expansion in the area. Figure 18 shows only the backbones and the secondary network with the ramifications to the areas. No further branches were considered. Moreover, the direct link between the users and the network is assumed to take place through the branches and not the sub-branches, otherwise, the amount of data would be difficult to manage.

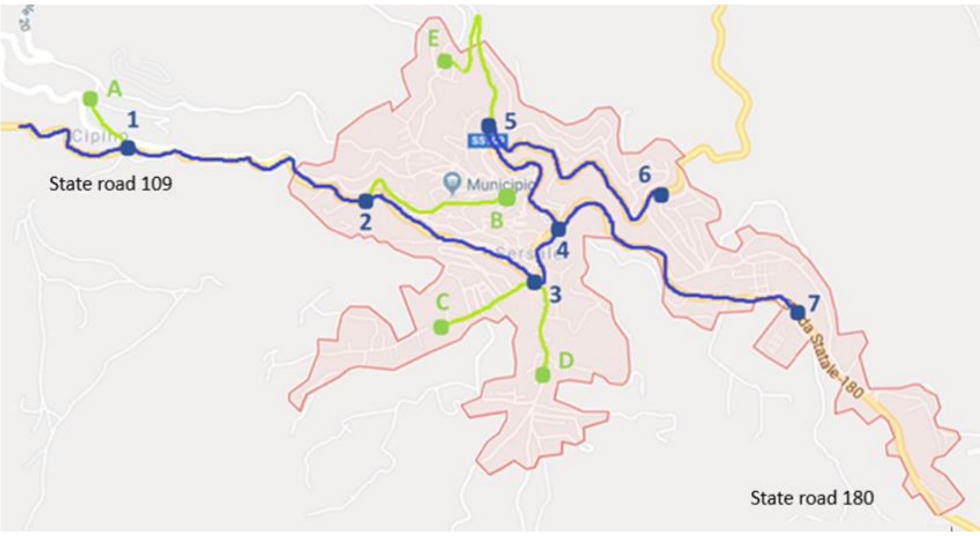


Figure 18. Path of the main pipelines (blue) and the secondary branches (green) of the DHN.

Points A, B, C, D, E, 6, 7 identify the different areas. The roads (identification name, carriageway width, and maximum height difference), the length data of pipelines and their ramifications are useful for the pipeline sizing. The definition of the total surface area of the Sersale territory covered by the DHN and the required pipeline's length allows the computation of the surface and mass flow rates of water required to the DHN (Table 52). .

Table 52: Mass flow rates of water required to the DHN by the macro-areas of the village

| Macro-area | Mass flow rate [kg/s] |
|---|---|
| Area 1 | 6.491 |
| Area 2 | 200.922 |
| Area 3 | 27.036 |
| Area 4 | 71.196 |
| Area 5 | 7.681 |
| Area 6 | 80.902 |
| Area 7 | 13.944 |

The Simulink provides the following outputs: the yearly trend of the electric power required by the three categories of buildings, the thermal power required according to the building heat balance, and finally the effective thermal load. From the Simulink simulations, it was found that the district heating distribution network must be able to provide a total mass flow rate of water of 408 kg/s, a total thermal energy of 41100 MWh/year, shown in Figure 19. Note that the maximum power that must be guaranteed is equal to about 17 MW during the winter and 5.5 MW during the summer.

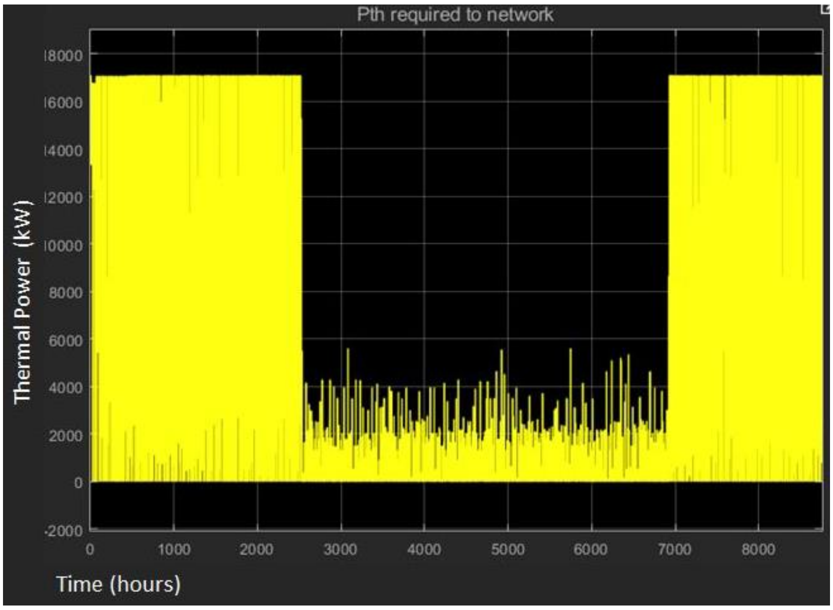


Figure19: Total thermal power required to the DHN by the macro-areas of the village during the year [kW]

The diameter of the pipes is calculated for each section of the network by the following expression:

$$D = \sqrt{\frac{4 \cdot G}{\varrho_{water} \cdot \pi \cdot u}} \cdot 1000$$

Equation 19.

where: G is the mass flow rate of water flowing through the pipe of the DH network (kg/s); $\varrho_{water}$ is the water density (kg/m$^3$); u is the fluid velocity, (2.5 m/s for speed along the backbones and 1.5 m/s for speed along the branches).
Therefore, the selected technology consists of steel pipes with plastic sheath whose thermal insulation is made of polyurethane rigid foam. The geometrical and thermal characteristics of the DHN pipes are shown in Table 53.

Table 53: Geometrical and thermal characteristics of the DHN pipes selected from a commercial catalogue

| | Extremes | Lenght | G | Chosen D | s iso | H |
|---|---|---|---|---|---|---|
| | | [m] | [kg/s] | [mm] | [mm] | [W/mK] |
| MAIN PIPES | 0-1 | 4000 | 408.17 | 456 | 101 | 0.277 |
| | 1 - 2 | 850 | 401.68 | 452 | 86 | 0.344 |
| | 2 - 3 | 600 | 200.68 | 320 | 72 | 0.268 |
| | 3 - 4 | 200 | 102.54 | 229 | 64 | 0.251 |
| | 4 - 5 | 500 | 88.59 | 212 | 64 | 0.251 |
| | 5 -6 | 900 | 80.91 | 203 | 48 | 0.251 |
| | 4 - 7 | 1000 | 13.95 | 84 | 36 | 0.186 |
| BRANCHES | 1- A | 270 | 6.49 | 74 | 36 | 0.186 |
| | 2 - B | 500 | 201.00 | 413 | 87 | 0.344 |
| | 3 - C | 350 | 27.04 | 152 | 41 | 0.239 |
| | 3 - D | 300 | 71.10 | 246 | 64 | 0.251 |
| | 5 - E | 600 | 7.68 | 81 | 36 | 0.186 |

The total power requirements of the users in the village are calculated using two sum operators inside Simulink. The results of the sums are then integrated to obtain the global requirements in terms of energy.

## The CHP biomass plant

As aforementioned, the cogeneration plants of the energy micro-grid rely on the steam turbine technology. The plant's cogeneration arrangement is indeed realized by introducing a heat exchanger downstream of the turbine. This component can recover the condensation heat of the expanded steam for the heating of the distribution network water, implementing a back-pressure configuration of the steam turbine plant.

The Simulink simulation aims to quantify and to obtain the hourly trend of the following parameters along the year:

- Useful thermal power produced by the CHP biomass plant and by the boiler and their sum (kW);
- Useful electric power produced by the steam power plant (kW);
- Total useful thermal and electric energies (kWh/year).

The Simulink model of the plants requires the definition of the following parameters (as the inputs to the energy generation system block): the operation schedule of the plant; the environmental temperature (°C); the temperature of water stored inside the network accumulator (°C); the electric power requirements of the users which could be provided by the plant (kW).

Different blocks are defined in the energy model, described by the several thermo-physical equations. Those have the aim to identify the transformations of the working fluids such as the thermo-physical states at the inlet and the outlet of each plant component as well as the thermal power exchanges.

Also, the total amount of woodchips needed for the operation of both the CHP plant and the integrative boiler is calculated (tons per year).

Therefore, the nominal electric power of the plant has been set at 2.5 MW considering the needs of the village which reaches a maximum of about 2.4 MW. In this way, the simultaneous operation of the two power plants would be able to cover the peaks of the village’s electric power demand.

The electric efficiency of CHP biomass plant is equal to 0.13, a value which follows the indications reported in the literature [136], which shows the electric efficiency of different CHP plants as a function of several parameters.

On the other hand, an auxiliary boiler is essential to cover the peaks for the thermal power demand. The boiler chosen for this study has a nominal thermal energy of about 29 MWh/year and a rated efficiency of 0.85. The production of the entire energy generation system is synthesized in terms of energies in Table 54, together with the woodchips consumption.

Table 54: Energy production and fuel consumption of the energy generation system

| | | |
|---|---|---|
| Produced electric energy | [MWh/year] | 6625 |
| Produced thermal energy (CHP) | [MWh/year] | 22470 |
| Produced thermal energy (Boiler) | [MWh/year] | 29540 |
| Total Produced thermal energy | [MWh/year] | 52010 |
| Cogeneration ratio | - | 0.29 |
| Woodchips consumption (CHP plant) | [t/year] | 14880 |
| Woodchips consumption (Boiler) | [t/year] | 10220 |
| Total woodchips consumption | [t/year] | 25100 |

## 3.5.3 Energy microgrid

The simulation of the energy microgrid has the objective to prove its resiliency. The differential equation, shown in (6), is then used to describe the dynamic behavior of the system. The result is the time trend of the temperature of the water circulating in the networks.

$$\frac{dT_{network\ water}}{dt} = \frac{Q_{aux} - Q_{load}}{c_{p,w} \cdot \varrho_w \cdot V_{network\ water}}$$

Equation 20.

where $Q_{load}$ represents the total thermal power requirements of the urban centres and it already takes into account the heat losses occurring along with the network; $Q_{aux}$ is the total thermal power released to the water of the network after the CHP plants and boilers operation; $V_{network\ water}$ is the volume of water contained inside the network pipes.

The model developed in Simulink for the energy microgrid simulation contains the following subsystems:

- “Weather data” and “Profiles and schedules” blocks: these two blocks contain the climate conditions simulator and information about the schedule for the CHP plants operations;

- “Calculation of energy requirements of the villages”: the outputs from the subsystem are the annual electric power profiles required by each village and the trend of the thermal power requested by the users of the DH network. The load curves are derived for every single village and then combined to obtain the entire micro-grid;
- Six “Energy generation system” blocks: each block represents the group of the CHP plant and the auxiliary boiler used to produce electricity and heat for the single village;
- “Global network” block: in order to simplify the model and to reduce the simulation time, the distribution network, which would serve all the six villages, is simulated as a physical water storage tank.

### 3.5.4 Results of the energy microgrid

In this section, results are reported for the entire energy microgrid. Moreover, the author want to investigate the resilience theme. The energy power plants in fact may be subject to faults, malfunctions, or necessary maintenance operations which may cause their shutdown. The network, therefore, is resilient if it manages to maintain the operation even in similar cases, completing its task consisting of the fulfilment of customers’ heat and electricity requests.

Simulations with Simulink are carried out, considering the possibility that at least one of the plants stops. The cases in which more than one system goes off are excluded from the simulations because they are not considered probable. Two different configurations are described for sizing purposes:

- Case A: if a plant goes off, there is an increase in the production of the heat from the remaining operative energy generation systems. This is necessary to satisfy the higher thermal load request from the network. It is assumed that the electrical and thermal production is divided among the remaining cogeneration plants, so the oversizing in production regards only the cogeneration systems, while the boilers keep its dimensions unchanged compared to the base case.
- Case B: both CHP plants and boilers are oversized compared to the base case, in which no plant shutdown is expected.

### Power and energy requirements of the urban centres included in the microgrid

The maximum power requirements for the entire energy microgrid are reported in Table 55. The maximum value of the thermal power required by the village users is showed, combined with the power lost for heat dispersion along the pipelines. The user's needs are responsible for a total of 6 MW of electric power and more than 46 MW of thermal power during the winter. Finally, the annual energy requirements are listed for the different urban centres, together with the resulting total amount for the entire energy microgrid.

Table 55: Power and energy requirements of the villages included in the energy micro-grid

| | Max electric power required | Max thermal power required | Required electric energy | Required thermal energy |
|---|---|---|---|---|
| | [kW] | [kW] | [MWh/year] | [MWh/year] |
| Sersale | 2400 | 19172 | 11360 | 40480 |
| Cerva | 527 | 4267 | 2303 | 12580 |
| Petronà | 1300 | 10000 | 6393 | 29320 |
| Andali | 600 | 4758 | 2806 | 13880 |
| Zagarise | 745 | 5870 | 3204 | 17960 |
| Magisano | 450 | 2790 | 2637 | 8687 |
| TOTAL (Simultaneous) | 6018 | 46776 | 28703 | 122907 |

From the maximum thermal power required by the users of a village, it is possible to calculate, as was done for the individual pipes of the Sersale network, the total mass flow rate of water circulating in the village network, considering that water temperature variation equal to 10 °C.

### Base case: CHP biomass sizing

The first simulation is carried out sizing the CHP biomass plants according to the electric energy demand of the single villages, as already done for the case of Sersale. Moreover, an electric load tracking allows to better guide the cogenerator functioning. The auxiliary boilers are introduced to satisfy the peaks of the thermal power requirements. The simulation results about the energy production of the plants are synthesized in Table 56.

Table 56: Energy production by the CHP plants and boilers of the microgrid – Base case

| | Produced electric energy | Produced thermal energy (CHP) | Produced thermal energy (Boiler) | Total Produced thermal energy | Cogeneration ratio |
|---|---|---|---|---|---|
| | [MWh/year] | [MWh/year] | [MWh/year] | [MWh/year] | - |
| Sersale | 6625 | 22470 | 29540 | 52010 | 0.29 |
| Cerva | 2153 | 6851 | 5579 | 12430 | 0.31 |
| Petronà | 4969 | 15920 | 13130 | 29050 | 0.31 |
| Andali | 2153 | 6851 | 5251 | 12100 | 0.31 |
| Zagarise | 3312 | 10540 | 9190 | 19730 | 0.31 |
| Magisano | 2153 | 6851 | 4923 | 11770 | 0.31 |

**Case A: oversizing of the CHP biomass plants**

To determine the required oversizing of the cogenerators, Simulink simulations of the energy microgrid performance in six different operating conditions are performed. This situation occurs in case the energy generation systems of the villages switched off one by one. Each case is considered individually, and the following tables summarize the sizes of the CHP plants which should be adopted to face the lack of heat production by the stopped CHP and boiler group (highlighted in grey in Table 57). Finally, the corresponding energy production is also reported.

Table 57: Max power produced by CHP and boiler for all scenarios - CASE A

| **Scenario** | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| | Max $P_{th}$ produced by CHP+boiler | Max $P_{th}$ produced by CHP+boiler | Max $P_{th}$ produced by CHP+boiler | Max $P_{th}$ produced by CHP+boiler | Max $P_{th}$ produced by CHP+boiler | Max $P_{th}$ produced by CHP+boiler |
| | [kW] | [kW] | [kW] | [kW] | [kW] | [kW] |
| Sersale | 0 | 17850 | 20060 | 17850 | 20060 | 17850 |
| Cerva | 10520 | 0 | 8317 | 6155 | 7190 | 6155 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Petronà | 15060 | 11740 | 0 | 11740 | 11740 | 11740 |
| Andali | 10450 | 6025 | 8237 | 0 | 6025 | 6025 |
| Zagarise | 13860 | 9437 | 9437 | 9437 | 0 | 9437 |
| Magisano | 8187 | 5975 | 7081 | 5975 | 7081 | 0 |

It can be noted that the sizes of the CHP plants identified for the scenarios 2, 4, and 6 are equal since the involved villages showed similar heat generation capacity also in case all the plants were on. These sizes are the smallest compared to scenarios in which Petronà or Zagarise plants are switched off and particularly compared to Scenario 1 (Sersale power plant shutdown). Consequently, these villages are those which host the largest energy generation systems, whose energy microgrid shutdown would be more critical.

Once the new configuration of the microgrid system has been identified, it is necessary to verify if the adoption of the new sizes guarantee the heat distribution inside the networks. Among this, a bypass of the turbine’s steam in the CHP plants towards the condenser must be foreseen.

This is necessary to avoid excess heat production by heat exchangers that cause the network imbalance. In general, the steam turbine plants work at the rated conditions as regards the electricity generation, even if occurs an excess in production that could be selling to the national electric distribution grid. These operating conditions (described in Table 58) justify the higher cogeneration ratios obtained for case A.

Table 58: Energy production by the CHP plants and boilers of the microgrid – Case A

| | Produced electric energy | Produced thermal energy (CHP) | Produced thermal energy (Boiler) | Total Produced thermal energy | Cogeneration ratio |
|---|---|---|---|---|---|
| | [MWh/year] | [MWh/year] | [MWh/year] | [MWh/year] | - |
| Sersale | 8281 | 13270 | 29540 | 42810 | 0.62 |
| Cerva | 6625 | 10620 | 5579 | 16190 | 0.62 |
| Petronà | 8281 | 13270 | 13130 | 26400 | 0.62 |
| Andali | 6625 | 10.539 | 5251 | 15790 | 0.68 |
| Zagarise | 8281 | 13270 | 9190 | 22460 | 0.62 |
| Magisano | 4969 | 7908 | 5087 | 12990 | 0.63 |

### Case B: oversizing of the CHP biomass plants and auxiliary

The procedure adopted for case A is then used to define an alternative resilient arrangement of the microgrid: the sizes (Tables 59, 60) of both cogenerators and auxiliary boilers are modified, increasing the seizes concerning the base case. The choice is based according to the results of the single test simulating the grid when one of the energy production units is not operating, as shown in Table 59.

Table 59: Max power produced by CHP and boiler for all scenarios - CASE B

| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|---|---|---|---|---|---|---|
| | max $p_{th}$ produced by chp+boiler | max $p_{th}$ produced by chp+boiler | max $p_{th}$ produced by chp+boiler | max $p_{th}$ produced by chp+boiler | max $p_{th}$ produced by chp+boiler | max $p_{th}$ produced by chp+boiler |
| | [kW] | [kW] | [kW] | [kW] | [kW] | [kW] |
| Sersale | 0 | 17850 | 17850 | 17850 | 17850 | 17850 |
| Cerva | 9617 | 0 | 7419 | 5854 | 7419 | 5854 |
| Petronà | 12850 | 10640 | 0 | 10640 | 10640 | 10640 |
| Andali | 9637 | 5876 | 7425 | 0 | 5876 | 5876 |
| Zagarise | 11850 | 7425 | 9637 | 7425 | 0 | 7425 |
| Magisano | 9637 | 5876 | 6540 | 5876 | 5876 | 0 |

In this case, the chosen sizes for the CHP plants correspond to the worst scenario (Scenario 1, when the largest power plant of Sersale is switched off). However, the sizes are lower than those identified in case A. The increased production capacity of auxiliary boilers of this configuration allows to face possible failure events better to the previous one. Moreover, the sizes of the boilers are also oversized: the boilers have to ensure the correct operation of the global DHN, when the base case size of the CHP plants and the energy plant of Cerva, Andali or Magisano are off. Then, it has been established the new cogenerators sizes, to cover the other three possible scenarios (Sersale, Petronà, or Zagarise shutdown). By following this criterion, the oversizing of the auxiliary boilers is limited and aimed to cover the less critical scenarios. Findings of the total electric and thermal energy production yearly trend of network water temperature are shown in Table 60.

Table 60: Energy production by the CHP plants and boilers of the micro-grid – Case B

| | Produced electric energy | Produced thermal energy (CHP) | Produced thermal energy (Boiler) | Total Produced thermal energy | Cogeneration ratio |
|---|---|---|---|---|---|
| | [kWh/year] | [kWh/year] | [kWh/year] | [kWh/year] | - |
| Sersale | 6625 | 11060 | 29540 | 40600 | 0.60 |
| Cerva | 4969 | 7391 | 9846 | 17240 | 0.67 |
| Petronà | 6625 | 12290 | 13130 | 25420 | 0.54 |
| Andali | 4969 | 7391 | 9846 | 17240 | 0.67 |
| Zagarise | 6625 | 9913 | 9846 | 19760 | 0.67 |
| Magisano | 4969 | 7391 | 9846 | 17240 | 0.67 |

Finally, a comparison of the different analysed scenarios can be developed based on energy production. The maximum electric power generation occurs for case A, as expected since the cogenerators' sizes are the largest. It is then followed by case B for which both CHP plants and boilers are oversized. The minimum value is attested for the base case. Case A also generally shows a higher thermal production using only cogeneration for the other microgrid configurations.

## 3.6 Application of the smart methodology: QIMM

The application of the smart methodology is described in the following paragraphs. Scenarios considered in this study are in total six: the base one, the resilience type A and the resilience type B. All of them are evaluated for the purchased and self-product woodchip, as it was done during the previous simulations. Table 61 summarize those smart strategies with a nomenclature.

Table 61: Smart scenarios

| Base | Base1 | ResA | ResA1 | ResB | ResB1 |
|---|---|---|---|---|---|
| **Base strategy (woodchip purchased )** | **Base strategy (woodchip self-product)** | **Resilience strategy A (woodchip purchased )** | **Resilience strategy A (woodchip self-product)** | **Resilience strategy B (woodchip purchased )** | **Resilience strategy B (woodchip self-product)** |

A set of smart indicators were defined to assess which energy plant obtain the major positive impact on the all smart field. The Excel database elaborated by the author contains 22 indicators. A brief description of them is reported below.

### 3.6.1 Smart and resilient performance indicators

Indices are grouped into the 5 smart axes: Energy, Environmental, Economy, Community and Mobility. Moreover, other six smart and resilience indicators are developed in order to better quantify the impact of resilient scenarios.

**Smart Energy indicators**

Two smart energy performance indicators were taken from a recent work [126], which are described below.

The Gross Thermal efficiencies (GTE):

$$GTE\ (\%): \frac{Heat\ produced}{PE\ Consumed\ in\ \boldsymbol{ex\ post}\ scenario}$$

GTE is the ratio between the total thermal energy produced (sum of the CHP and auxiliary boiler heat energy production) and the total primary energy (PE) consumed after (*ex post* scenario) the energy microgrid realization.

The Electric efficiencies (EF):

$$EF\ (\%): \frac{Electricity\ produced}{PE\ Consumed\ in\ cogeneration\ \ section\ of\ \boldsymbol{ex\ post}\ scenario}$$

EF is the ratio between the total electric energy produced (only the CHP electric energy production) and the total primary energy (PE) consumed after (*ex post* scenario) the energy microgrid realization.

One indicator related to the woodchips consumption was defined by the author, in order to highlight which scenario consumed the highest primary source quantity.

The Biomass (woodchips) Consumption (BC):

$$\mathrm{BC}\left(\frac{t}{year}\right): Sum\ of\ CHP\ and\ auxiliarly\ boiler\ woodchips\ consumption$$

**Smart Environment indicators**

Another two smart environment performance indicators were taken and elaborated from the work of [126], which are described below.

The $CO_2$ emission saving (CO₂ Saving):

$$\mathrm{CO_2\ Saving\ (\%)}: (CO_2\ emission\ saving\ )/(PE\ consumed\ in\ \boldsymbol{ex\ ante}\ scenario)$$

The $CO_2$ emissions savings were calculated yearly and by the comparison of the two configurations, before (*ex-ante* scenario) and after (*ex post* scenario) the energy microgrid installation. For the *ex-ante* scenario, it was assumed that the residential buildings used natural gas boiler or chimney (two hypothetical *ex ante* scenarios), the commercial and office ones used only the natural gas boiler. Regarding the electricity, all the villages are connected to the national Italian electric grid. Moreover, benefits deriving from the power generation are taken into account during the emission saving calculation. The same explanation is valid for the Particulate (PM) emission saving indicator.

The PM emission saving (PM Saving):

$$\mathrm{PM\ Saving\ (\%)}: (PM\ emission\ saving\ )/(PM\ emission\ in\ \boldsymbol{ex-ante}\ scenario)$$

Below are reported the emission factors useful for the calculation of the previous environmental indicators and they refer to several references in literature.

Table 62: Assumption for pollutants ($CO_2$ and PM) emission factors.

| Energy Source | $kgCO_2/kWh$ | mgPM/kWh | References |
|---|---|---|---|
| Woodchip | 0.015 | 515 | [94, 126] |
| Natural gas | 0.204 | 0.72 | [126] |
| Wood for chimney | 0.010 | 515 | Biomass Trade [94, 126] centres |

| | | | |
|---|---|---|---|
| Electricity from the national grid | 0.489 | 3.2 | [126] |
| DHN | 0.3 | - | (report Caserini) [94, 126] |

Another aspect that it is involved in the environmental performance is the energy source transportation. Among this, the $CO_2$ emission consumed per km for woodchips transport (WTr) indicator was elaborated.

The Emission of Biomass (woodchips) Transport (EBT):

EBT ($kgCO_2$): $The\ total\ amount\ of\ kgCO_2\ consumed\ per\ km\ for\ woodschips\ transport.$

This indicator was calculated for the two scenarios: purchased and self-production of woodchip. For the first case, it was assumed that the woodchip production point is located in the city of Catanzaro, due to the real presence of this commercial activity type (25). Then it was possible to calculate the distance mean (Km) of those villages respect to this location. For the other solution (the woodchips self-production), Sersale was chosen as the reference village for the production of woodchips. Therefore, the distance from Sersale to the other communities is consistently reduced. Data regarding the $CO_2$ emission factor of heavy vehicles are taken from (26).

**Smart Economy indicators**

Among the comic evaluation, seven smart economy indicators were investigated, such as the pay-back time, the total investment and so on. Data related to this study are taken and elaborated from a previous work of [137] and an example of their calculation is reported in the appendix.

The total Revenues (RE):

RE (€/year): $Sum\ of\ the\ energy\ sale\ to\ costumers\ and\ to\ GSE$

Staring from the average energy consumption of the villages current state, the cost for heating and electricity was done. Then it was possible to calculate the economic saving for the users (around -45%). For the final revenues are taking into account the energy sale to customers (both thermal and electrical) and the electricity sale to GSE.

The Annual Cost (AC):

$$\text{AC (€/year)}: Sum\ of\ the\ total\ running\ costs$$

Running cost involved the operation and maintenance and the fuel cost for each energy system components (the CHP, the auxiliary boiler, the distribution system). Moreover, the salaries of workers for the plant installation are taken into account (see Appendix).

The total Investment (TI):

$$\text{TI (€)}: Sum\ of\ the\ total\ investements$$

Similarly, the TI is the whole investment for the energy microgrid realization (see Appendix).

The Net Present value (NPV):

$$\text{NPV (€)}: \sum(CFn\ /\ (1\ +\ i)n) - Initial\ Investment$$

Where $n$ is the period which takes values from 0 to the nth period till the cash flows ending period, the $CF_n$ is the Cash flow in the nth period and $i$ is the discounting rate (in this study is set to 4%).

Then, the Internal Rate Return is calculated and it represents the rate at which the NPV is equal to zero, e.g. the discount rate at which the present value of cash flows generated by a specific activity equals the expenditure required for the purchase of the same activity.

The Internal Rate Return (IRR):

$$\text{IRR (\%)}: \frac{\text{Cash flows}}{(1+r)^\wedge i} - Initial\ investement$$

Where *Cash flows* are the period which takes values from 0 to the nth period till the cash flows ending period, $r$ is the time period and $i$ is the discounting rate.

The Pay Back Period that calculates the number of years needed to recover the initial outlay of an investment project, practically the first deadline in which a sign reversal occurs in cash balances.

The Pay Back Period (PBP):

$$PBP\ (years):\ (Initial\ investement)/(Cash\ flow)$$

Finally, the EBITDA (Earnings Before Interest, Taxes, Depreciation and Amortization), is a financial performance index, calculated subtracting the annual costs from the revenues.

The EBITDA (EBITDA):

$$\text{EBITDA (€)}: Total\ revenues - Annual\ cost$$

**Smart Community indicators**

Among the community field, an indicator was developed able to quantify the advantages for the local users to implement the smart scenarios.

The number of Employers (EM):

$$\text{EM (unit)}: Total\ number\ of\ workers\ employment$$

Estimation was done to analyse how many numbers of workers are required for installing both the energy system and the woodchip industry (referring to the woodchip self-production).

**Smart Mobility indicators**

Although the mobility sector is not the focus of the smart scenarios, a smart performance indicator was investigated refers to woodchip transport. Scenarios that foresee the use of purchased woodchip are directly involved in this study.

The Biomass (woodchip) Transport (BT):

$$\text{BT (Km)}: Kilometres\ consumed\ for\ the\ woodchips\ transport$$

## Smart resilience indicators

To evaluate the resilience characteristics of the proposed scenarios, a list of resilience indicators regarding all the smart field are elaborated. As aforementioned, the resilience theme contains several definitions and applications in a wide range of aspects. In this work, the focus is the resilience of the energy system plant. Few works in literature [103] proposed specific indicators able to described its potentialities.

In this framework, the aim is to investigate the benefit of an energy system if it can overcome a failure event and, on the other hand, the disadvantages if the energy system is not resilient. Therefore, indicators regarding the environment, the economy, the community and the mobility filed are calculated starting from the problems that occur during a black-out. Assumptions for managing this event were done by the author, keep in mind that most of them are supported by references.

Finally, the resilient energy indicator aims to highlight the benefit of a resilient system in terms of the available energy for the users.

### Energy Axis

Two indicators regarding the resilience aspect were done. Both of them express the energy (thermal and electrical) availability if one village's plant is shutdown. In other words, the amount of energy available for the citizens during a black-out event.

Electric energy availability (ResEN1):

$$ResEN1(\%)\colon \frac{Electricity\ produced\ during\ blak-out\ events}{Electricity\ required\ by\ users}$$

Thermal energy availability (ResEN2):

$$ResEN2(\%)\colon \frac{Heat\ produced\ during\ blak-out\ events}{Heat\ required\ by\ users}$$

**Environmental Axis**

Moreover, two resilience indices were proposed to quantify the environmental consequences of a failure event. Private and public (e.g. ENEL E-Distribution) users damages were separately investigated, highlighting the impact in term of emission caused by the use of an emergency energy generator during this black-out.

The Resilience Environmental indicator 1(ResENV1):

$$\text{ResENV1 (kgCO}_2\text{)}: kgCO_2\ consumed\ by\ the\ emergency\ generator\ for\ 1\ hour\ and\ 30\ min$$

E-Distribution Enel was assumed as the leading manager of the CHP plants. Therefore, the nearest Enel office is located again in Catanzaro. During the black-out users have to face with it, using s private emergency generator, waiting around 1 hour and half the Enel energy generator (the aforementioned timing was calculated knowing the mean distance between Catanzaro and the communities understudy).

An office with 100 sq. and a commercial space of 100 sq. consumed around 25 kW (27), therefore it was chosen the “Gruppo Elettrogeno 40 kVA soundproofed” (28). Then it was possible to calculate the $CO_2$ consumed. This generator used as a fuel the Diesel one; the emission factor of Diesel is 0,25 $kgCO_2/kWh$.

The Resilience Environmental indicator 2 (ResENV2):

$$\text{ResENV2 (kgCO}_2\text{)}: kgCO_2\ consumed\ by\ the\ ENEL\ generator\ for\ 1\ hour$$

**Economy Axis**

Regarding the economy field, the cost of generator rental and fuel by the ENEL industry was done. It is well known that the price of this kind of generator, characterized by a consistent size of power, is very high. For this study, it was chosen as an emergency generator of 1.280 kW (29).

To cover the energy request for an entire village, two generators are necessary. Knowing that this indicator quantifies the price for the day.

The Resilience Economic indicator (ResEC):

$$\mathrm{ResECON}\ (€)\!: Total\ cost\ (rental + fuel) of\ the\ generator\ support\ by\ ENEL$$

**Community Axis**

As aforementioned for the environment indicators definition, the private users are supposed to have an emergency generator while they are waiting for the energy manager. Knowing the price (30) and the Diesel cost (31), it was possible to calculate it.

The Resilience Community indicator (ResCOM):

$$\mathrm{ResCOM}\ (€)\!: Total\ cost\ (investement + fuel) of\ the\ generator\ support \\ by\ private\ users$$

**Mobility Axis**

The average distance between the nearest ENEL center (located in the city of Catanzaro) and the other villages is the mobility performance indicators, aiming to highlight the km consumed by the heavy vehicle due to the black-out event.

The Resilience Mobility indicator (ResMOB):

$$\mathrm{ResMOB}\ (\mathrm{Km})\!: Total\ amount\ of\ Km\ consumed\ by\ the\ vehicle\ during \\ the\ black-out$$

## 3.6.2 Quantitative Incidence Matrix

Table 63 below summarizes the aforementioned indicators calculated for each smart scenario. It has been pointing out that some resilient indicators obtained a value of zero because they highlight the negative aspects of a non-resilient energy system. Therefore, the resilient scenario is not affected by them (e.g. ResCOM indicator).

Table 63: List of strategies and indicators.

| **AXIS** | **Indices** | **Indicator** | Base | Base1 | ResA | ResA1 | ResB | ResB1 |
|---|---|---|---|---|---|---|---|---|
| **ENERGY** | **Energy plant** | GTE (%) | 1.73 | 1.73 | 1.72 | 1.72 | 1.73 | 1.73 |
| | | EF (%) | 1 | 1 | 1.88 | 1.88 | 1.51 | 1.51 |
| | **Woodchip** | BC (t/year) | 69633.53 | 69633.53 | 120152.06 | 120152.06 | 95038.00 | 95038.00 |
| | **Resilience** | ResEN1(%) | 0.00 | 0.00 | 1.50 | 1.50 | 1.21 | 1.21 |
| | | ResEN2(%) | 0.00 | 0.00 | 1.11 | 1.11 | 1.12 | 1.12 |
| **ENVIRONMENT** | **Energy plant** | CO2 saving (%) | 257.72 | 257.72 | 535.69 | 535.69 | 429.53 | 429.53 |
| | | PM saving (%) | 8.37 | 8.37 | 15.87 | 15.87 | 13.01 | 13.01 |
| | **Woodchip** | EBT (kgCO2) | 43.75 | 43.75 | 6.36 | 6.36 | 6.36 | 6.36 |
| | **Resilience** | ResENV1 (kgCO2) | 11.25 | 11.25 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | ResENV2 (kgCO2) | 640.00 | 640.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **ECONOMY** | **Economical and financial analysis** | RE (€/year) | 5753780.00 | 5151700.00 | 7813150.00 | 6993090.00 | 7042320.00 | 6993090.00 |
| | | AC (€/year) | 3424708.24 | 2515931.67 | 5375362.15 | 3807275.96 | 2619765.06 | 2248368.65 |
| | | TI (€) | 14131206.00 | 14131206.00 | 21327844.00 | 21327844.00 | 19407111.00 | 19407111.00 |
| | | NPV (€) | 45932913.05 | 53842270.00 | 41539940.00 | 60830687.00 | 94645566.00 | 86828610.00 |
| | | IRR (%) | 0.11 | 0.14 | 0.11 | 0.14 | 0.23 | 0.22 |
| | | EBITDA (€) | 2329071.76 | 2635768.33 | 2437787.85 | 3185814.04 | 4422554.94 | 4119441.35 |
| | | PBP | 6.07 | 5.36 | 8.75 | 6.69 | 4.39 | 4.71 |
| | **Resilience** | ResECON (€) | 475.00 | 475.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **COMMUNITY** | **Employers** | EM (unit) | 170.00 | 185.00 | 200.00 | 215.00 | 215.00 | 200.00 |
| | **Resilience** | ResCOM (€) | 10324.80 | 10324.80 | 0.00 | 0.00 | 0.00 | 0.00 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **MOBILITY** | **Woodchip** | BT (km) | 75.70 | 75.70 | 11.00 | 11.00 | 11.00 | 11.00 |
| | **Resilience** | ResMOB (Km) | 35.70 | 35.70 | 0.00 | 0.00 | 0.00 | 0.00 |

Following the QIMM methodology, the Correction Factor has been developed to give the right interpretation for each indicator. If the impact of an indicator is negative, a -1 value will be assigned, if it is a positive value of 1 (see Table 65).

The energy indicators (GTE and EF) are positive since they represent the thermal and electrical efficiencies, while BC is negative since it is the total amount of biomass consumed by each plant. The resilient energy indicators (ResEN1 and ResEN2) are positive since they express the energy availability in case of a plant's failure. The first two environmental indicators (CO2 and PM saving) are positive because they represent the emissions saving reached by the plants. The other three (EBT, ResENV1, ResENV2) are negative since they respectively evaluate the emission of CO2 for biomass transport and the use of emergency generators. The economic ones such as RE, NPV, IRR and EBITDA are positive, quantifying the economical and finical benefit of the energy system installation. Conversely, the AC and TI are negative, highlighting the scenario's annual cost and the investment respectively. The resilient economy indicator is also negative since it represents the total cost of an emergency generator for covering the energy gap during the black-out. Regarding the community, the EM is positive since it expresses the increase of the number of workers for the plant installation; conversely, the ResCOM is negative, taking into account the user's expenses for the emergency generator. Finally, both the mobility indicators are negatively quantifying the negative impact of biomass transport, in term of Km.

Time and cost feasibility are reported in the tables below. Different assumptions have been made for timing and cost estimations. Data regarding the realization of the plant are extremely rare to find in literature. Therefore a simplification was made by the author, giving the worst score (equal to 0) to the scenarios with biomass self-production. The other scenarios obtained a qualitative score of 0.5 because the timing of those plants installations will be less compared to the realization of the plants for the woodchip production.

On the other hand, the economic feasibility is expressed by the total investment of each scenario (see Appendix).

Table 64: Cost estimations scores

| Strategy | Cost (€) | Score |
|---|---|---|
| Base | 17555915 | 0.34 |
| Base1 | 16647139 | 0.38 |
| ResA | 26703205 | 0.00 |
| ResA1 | 25135119 | 0.06 |
| ResB | 22026875 | 0.18 |
| ResB1 | 21655479 | 0.19 |

It is now possible to calculate the final score for the Incidence Matrix. As aforementioned, the scores range is between 5 and -5.

Table 65: Final scores of strategies and indicators.

| **Axis** | **Indices** | **Indicator** | Base | Base 1 | Res A | Res A1 | ResB | ResB 1 | CF |
|---|---|---|---|---|---|---|---|---|---|
| **ENERGY** | **Energy plant** | GTE (%) | 5 | 5 | -5 | -5 | -5 | -5 | 1 |
| | | EF (%) | 5 | 5 | -5 | -5 | -5 | -5 | 1 |
| | **Woodchip** | BC (t/year) | -5 | -5 | 5 | 5 | 1 | 1 | -1 |
| | **Resilience** | ResEN1(%) | -5 | -5 | 5 | 5 | 3 | 3 | 1 |
| | | ResEN2(%) | -5 | -5 | 4 | 4 | 5 | 5 | 1 |
| **ENVIRON MENT** | **Energy plant** | CO2 saving (%) | -5 | -5 | 5 | 5 | 1 | 1 | 1 |
| | | PM saving (%) | -5 | -5 | 5 | 5 | 1 | 1 | 1 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Woodchip** | EBT (kgCO2) | 5 | 5 | -5 | -5 | -5 | -5 | -1 |
| | **Resilience** | ResENV1 (kgCO2) | 5 | 5 | -5 | -5 | -5 | -5 | -1 |
| | | ResENV2 (kgCO2) | 5 | 5 | -5 | -5 | -5 | -5 | -1 |
| **ECONOMY** | **Economical and financial analysis** | RE (€/year) | -2 | -5 | 5 | 2 | 2 | 2 | 1 |
| | | AC (€/year) | 1 | -3 | 5 | 1 | -3 | -5 | -1 |
| | | TI (€) | -5 | -5 | 5 | 5 | 2 | 2 | -1 |
| | | NPV (€) | -4 | -2 | -5 | 0 | 5 | 3 | 1 |
| | | IRR (%) | -5 | -1 | -5 | -1 | 5 | 4 | 1 |
| | | EBITDA (€) | -5 | -3 | -4 | 0 | 5 | 4 | 1 |
| | | PBP | 1 | -1 | 5 | 2 | -5 | -3 | -1 |
| | **Resilience** | ResECON (€) | 5 | 5 | -5 | -5 | -5 | -5 | -1 |
| **COMMUNITY** | **Employers** | EM (unit) | -5 | -2 | 1 | 5 | 5 | 1 | 1 |
| | **Resilience** | ResCOM (€) | 5 | 5 | -5 | -5 | -5 | -5 | -1 |
| **MOBILITY** | **Woodchip** | BT (km) | 5 | 5 | -5 | -5 | -5 | -5 | -1 |
| | **Resilience** | ResMOB (Km) | 5 | 5 | -5 | -5 | -5 | -5 | -1 |
| Sum (multiple for CF included) | | | **-58** | **-44** | **16** | **37** | **62** | **54** | |
| Time feasibility | | | 0.5 | 0 | 0.5 | 0 | 0.5 | 0 | |
| Cost feasibility | | | 0.3 | 0.4 | 0 | 0.1 | 0.2 | 0.2 | |
| **Final Score** | | | -57.2 | -43.6 | 16.5 | 37.1 | 62.7 | 54.2 | |
| **Final Ranking** | | | **6** | **5** | **4** | **3** | **1** | **2** | |

The best scenario is the energy resilient case ResB, followed by ResB1. The third and fourth positions are occupied by the energy resilient case ResA1 and purchased one respectively. Base scenario, the non-resilience strategy, is attested on the last two positions, in which the worst one is the scenario with purchased biomass (Base). In general, the solution with the self-production of biomass obtained the higher score compared to the same solution with the purchased one.

This issue is not valid for the case ResB. Among this, a couple of considerations can be made. The aspects involved are two, the economy field and the technical characteristics of the energy plant. In term of revenues, the purchased biomass is not convenient for all scenarios. On the other hand, in term of annual cost, the woodchip self-produced is more convenient for the scenario ResA, in which the amount of biomass consumed is relevant due to the consistent oversizing of the CHP unit.

Moreover, the marginal cost of the biomass produced in loco is less compared to the purchased one, and those prices (see Tables i-ii-iii-iv-v in Appendix) are used for sailing the thermal and electrical energy to the users. Therefore, the EBITDA, NPV and IRR for the case ResB1 are lower compared to the scenario ResB (see Table 63). However, ResB and ResB1 showed for the rest of the smart axis, especially the energy and environment ones, the best performances. Conversely, the Base scenario could not guarantee the same performances in terms of resilience. In line with this, it could be interesting to understand how much the resilient performance indicators had given an impact on the smart ranking.

## 3.7 Results and Discussion

The author want to investigate if the impact of the resilience indicators could modify the previous smart ranking. Therefore, a new ranking was drafted, eliminating the resilience indices.

Table 66: Final scores of strategies and indicators (without resilient ones).

| **Axis** | **Indices** | **Indicator** | Base | Base 1 | Res A | ResA 1 | Res B | ResB 1 |
|---|---|---|---|---|---|---|---|---|
| **ENERGY** | **Energy plant** | GTE (%) | 5 | 5 | -5 | -5 | -5 | -5 |
| | | EF (%) | 5 | 5 | -5 | -5 | -5 | -5 |
| | **Woodchip** | BC (t/year) | -5 | -5 | 5 | 5 | 1 | 1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Resilience** | | | | | | | |
| **ENVIRONMENT** | **Energy plant** | CO2 saving (%) | -5 | -5 | 5 | 5 | 1 | 1 |
| | | PM saving (%) | -5 | -5 | 5 | 5 | 1 | 1 |
| | **Woodchip** | EBT (kgCO2) | 5 | 5 | -5 | -5 | -5 | -5 |
| | **Resilience** | | | | | | | |
| **ECONOMY** | **Economical and financial analysis** | RE (€/year) | -2 | -5 | 5 | 2 | 2 | 2 |
| | | AC (€/year) | 1 | -3 | 5 | 1 | -3 | -5 |
| | | TI (€) | -5 | -5 | 5 | 5 | 2 | 2 |
| | | NPV (€) | -4 | -2 | -5 | 0 | 5 | 3 |
| | | IRR (%) | -5 | -1 | -5 | -1 | 5 | 4 |
| | | EBITDA (€) | -5 | -3 | -4 | 0 | 5 | 4 |
| | | PBP | 1 | -1 | 5 | 2 | -5 | -3 |
| | **Resilience** | | | | | | | |
| **COMMUNITY** | **Employers** | EM (unit) | -5 | -2 | 1 | 5 | 5 | 1 |
| | **Resilience** | | | | | | | |
| **MOBILITY** | **Woodchip** | BT (km) | 5 | 5 | -5 | -5 | -5 | -5 |
| | **Resilience** | | | | | | | |
| Sum (multiple for CF included) | | | -23 | -9 | -18 | 3 | 29 | 21 |
| Time feasibility | | | 0.5 | 0 | 0.5 | 0 | 0.5 | 0 |
| Cost feasibility | | | 0.3 | 0.4 | 0 | 0.1 | 0.2 | 0.2 |
| **Final Score** | | | **-22.2** | **-8.6** | **-17.5** | **3.01** | **29.7** | **21.2** |
| **Final Ranking** | | | **6** | **4** | **5** | **3** | **1** | **2** |

Excluding the resilience indicators from the QIMM process, a couple considerations regarding those results can be made. In line with this, Table 67 shows clearly the changes in this raking compared to the original one.

Table 67: Comparison of both final rankings.

| Ranking | Original | No resilient indicators | Changes in No resilient indicators respect Original |
|---|---|---|---|
| **1** | ResB | ResB | = |
| **2** | ResB1 | ResB1 | = |
| **3** | ResA1 | ResA1 | = |
| **4** | ResA | Base1 | ↑ 1 |
| **5** | Base1 | ResA | ↓1 |
| **6** | Base | Base | = |

Similarly to the original ranking (Table 67), the first two positions are occupied by the ResB and the ResB1. As aforementioned, the ResB obtained higher score from the energy, environment and economic indexes but the difference between the score of ResB and ResB1 is lower in this case compared to the original ones. Moreover, the scenario Base1 reaches the fourth position; on the other hand, the ResA solution obtained a lower score, highlighting the impact of the resilient indicators on its score in the original ranking.

Summarizing, the scenarios with the purchased woodchip obtained a higher score compared to the original ranking. An exception is a case B, in which the benefit of the biomass purchased is too consistent, as explained in these paragraphs. Resilient indicators, therefore, have an impact on the ranking, particularly for the case ResA, helping this scenario to enhance better its quality in term of resilience; but their influence is not so strong to change completely the ranking. Finally, smart indicators conversely provide well-balanced results, especially for the best and worst strategies, giving a coherent framework with the analysis of the scenarios.

## 3.8 Conclusion

This work proposed a resilient energy microgrid, based on CHP biomass plant and a district heat networks, applied to a real case study, located in the mountain Italian region. Six communities are connected through the DHN, providing thermal and electrical needs. The CHP biomass plant uses the local woodchips, integrating the renewable source in the energy generation system. Simulations are carried out with the MATLAB/Simulink tool, able to create and modelled a dynamic energy/environmental system. The entire energy microgrid was developed starting from the Sersale village, calculating its thermal and electrical requirements and the final energy system size.

To develop a resilience energy microgrid able to face failures and blackout put, a final analysis concerning the oversizing of the energy system was done. Knowing the importance and the power of resilience in the communities, the other two configurations of this energy microgrid are proposed (Case A and Case B), increasing the size of the CHP biomass plant and the CHP and boilers, respectively.

Results for the base case are reported, highlight the essential role of the auxiliary boiler that ensures the thermal needs (around the 46 MW). Regarding case A, the best scenarios are 2, 4, and 6 since the involved communities showed similar heat generation capacity also in the case all the plants were on. The worst scenario is related to the Sersale's energy generation plant shutdown, being the largest village. Regarding the case B, it showed a similar trend for all the scenarios compared to case A but slightly reduced, thanks to the increased capacity of auxiliary boilers.

Once the QIMM approach is applied to the six scenarios (Base, Base1, ResA, ResA1, ResB and ResB1), a final smart ranking was obtained. In details, scenario ResB gained the highest scores in terms of energy, environmental and economic benefits, as smart and resilient indicators underlined. Finally, the impact of the resilient indicators, elaborated in this chapter, is balanced providing the right weight to all the scenarios but maintaining the worst and best strategies in the ranking.

Future developments will involve resilient aspects to expand their significance and influence in the QIMM process. Keeping in mind, this is the first step of this study to include the resilience theme, the next aim is to investigate the flexibility of this project to be adapted in another mountain context.

# Chapter 4

# SMART METHODOLOGY (QIMM): APPLICATION TO AN ITALIAN SUBURB

## 4.1 Introduction

Starting from the analysis of the problems that characterize the Italian suburbs, the application of the QIMM approach to a real peripheral area is presented in this last chapter. In literature, several studies underline the urgent request of the city's periphery, enhancing local and national projects to increase the quality of life in the suburbs. In this framework, the author propose a multifunctional centre development, characterized by modern technologies (both structural and plant) to implement energy efficiency and social aggregation, in line with the citizen's needs. Once the simulation model of alternative solutions, such as construction type, energy system and social services, was elaborated in Matlab/Simulink, the application of a smart methodology was necessary to draft the priority ranking of the various strategies. Results highlight which solution obtained a positive impact on the overall smart axes, providing a useful approach for designers to plan a sustainable and smart project.

## 4.2 State of art of projects for the suburbs redevelopment

In the last century, phenomena of the conurbation and uncontrolled migratory flows, combined with a lack of planning and absent governance, have led to a porous urban context, characterized by the clear contrast between the center and the periphery, [138] so much so that in the time the term periphery has increasingly taken on a negative meaning. In the Italian context, these areas are characterized by social marginality, unemployment, a lack of public services and the presence of organized crime [139]. Therefore, it is still essential to propose a redevelopment that pays attention to peripheral areas, to develop a

more socially and sustainable city. This process can be the result of a malleable and fluid bottom-up method, not pre-established, but built starting from the real needs expressed by the citizens themselves who become the promoters of the design of the new face of the city, thanks to the distribution of a survey [140]. On the other hand, Multi-Criteria Decision Analysis (MCDA) [141] can be used to solve a wide range of city problems or a model that reproduces the possible behaviour of the citizens, based on empirical data [142], especially when the intervention dimensions become prohibitive for direct field research.
For the requalification of neglected areas, the UN (United Nation) ratified in 2015 an Agenda for Sustainable Development aimed at resolving the polarization of urban contexts between central and peripheral neighborhoods. Over the years, numerous projects have been presented and implemented, such as the one on the South Park of Milan [143] or the one on the roman district of Bastogi [144]. Regarding the [143], the energy efficiency of buildings and alternative mobility are the key points of the redevelopment, aimed at improving the lives of citizens, thanks to better environmental and infrastructural conditions; the second one [144] starting from the collaboration of the citizens and local authorities, well-being was studied as an expression of the degree of education, health and social inclusion, implementing a methodology aimed to reduce the inequality between peripheral and central areas.

## 4.3 Aims and Methodology

The presented work has the aim of applying the theoretical principles of Smart Cities for the redevelopment of a large green area located in the centre of Tor Bella Monaca. To respond to the local problems, the creation of a multifunctional centre, powered by renewable sources and equipped with innovative technologies, was planned. This new complex will host several activities for different citizen ages: from child to elderly people. A comprehensive model was developed capable of describing both the plants and the structural elements, to compare the alternatives considered, both from an energy and economic point of view. Furthermore, thought the Performance Indicators calculation, it was possible to analyse deeply the results obtained.

Finally, a global ranking of the proposed strategies will be elaborated which shows the impact and the transversal effectiveness of the various interventions in a smart perspective. Moreover, this smart process could be applied to different urban context, highlighting problems and identifying smart solutions, in a more modular and organic way.

Summarizing, the scope of this work is to:

- Enhance the periphery area of Tor Bella Monaca, in line with the citizen's needs.
- Develop a multifunctional centre, powered by renewable sources and equipped with innovative technologies.
- Apply the QIMM smart approach, able to identify the best smart solutions elaborated for this case.

As aforementioned, this research is focused on the inclusion of stakeholders within the steps of the method, to consider more concretely the problems expressed by the citizens themselves. The steps of this methodology are briefly reported below:

1. Preliminary planning: the project was born with the scope to apply the Smart theory to the context of Tor Bella Monaca, a suburb area of Rome;
2. Smart axes definition: those smart fields are the macro-area investigated [11] (Smart Economy, Smart People and Living, Smart Mobility, Smart Environment and Smart Energy);
3. Problem categorization through a survey: to obtain data and information relating to the project area, a questionnaire was created and distributed, physically and electronically, to a wide range of citizens. Then the results were analysed and tabulated to have a global view of the problems expressed and to outline the guidelines for Smart design;
4. Planning of strategies starting from the results of the survey, several interventions were drawn up to solve the critical issues organically and effectively;
5. Simulation of strategies: thanks to the use of Matlab/Simulink and Dialux tools, the proposed interventions have been simulated and analysed;
6. Smart ranking through the Performance Indicators and their standardization: thanks to the PI, it was possible to define the priority ranking

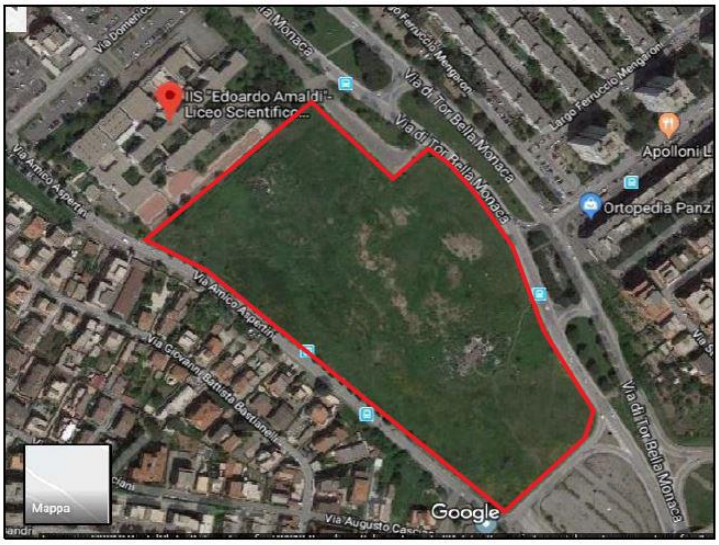
of the proposed strategies, highlighting which of them achieved a positive or negative impact, according to the methodology.

## 4.5 Case study: Tor Bella Monaca, Rome

The smart project area is developed in Tor Bella Monaca, a famous suburb of Rome. Located outside the Grande Raccordo Anulare of Rome, Tor Bella Monaca is a suburb, grown between the two main streets: via Casilina in South and via Prenestina in the North. This periphery is divided into two different zones. The first one "la Borgata" was built during the '40 years of 1900; the second zone was developed at the end of 1980, in which the popular residential complex was enhanced, hosting about 30.000 habitants. Nowadays, Tor Bella Monaca is still identified as a problematic roman suburb, in which innovative and ecological projects are welcomed to increase the quality of the of its habitants.

A central area of this periphery was chosen, being an important zone of green and historic monuments (hightailed in red in Figure 20).

Figure 20: Project's area.



## 4.6 Methodology application

According to the methodology described in the previous paragraphs and chapters, the first steps is the preliminary planning that involves  the analysis of the characteristics of the urban context.

### 4.6.1 Preliminary Planning

The intervention area (about 65390 $m^2$) is a municipal green area, in front of a high school and neglected parking, which hosts the remains of an ancient Roman villa. This area is now abandoned and intended for the occasional disposal of waste or the occasional residence of the homeless. The neighbourhood, in which the considered area is located, is a periphery characterized by the lack of specific social and job policies [145] and socio-technological attractiveness [146]. A series of problems can be identified, such as:

1. social exclusion
2. unemployment
3. crime
4. juvenile discomfort.

### 4.6.2 Smart axes identification

The definition of the smart axis was done, following the QIMM methodology. Five smart fields therefore are involved: Energy, Economy, Environment, Mobility and Living the campus.

### 4.6.3 Problem categorization through a Survey

The questionnaire was distributed both physically and electronically, to a heterogeneous sample, in terms of age and profession, made up of over 200 people belonging to the local population. In the survey (Table 68), people had to give a mark from 1 insufficient to 5 excellent for the questions asked.

Table 68: Survey.

| **Questionnaire** | |
|---|---|
| **Question 1: How do you judge…?** | **Mark** |
| Recreational activities | x |
| Health care | x |
| Waste management and recycling | x |
| Park and green areas management | x |
| Presence of green areas in the neighbourhood | x |
| Events of social aggregation | x |
| Social solidarity events | x |
| Educational activities with professional outlets | x |
| Youth gathering places | x |
| Neighbourhood abandonment level | x |
| **Question 2: How much those strategies could increase the quality of life for the neighbourhood …?** | **Mark** |
| Photovoltaic panels | x |
| Rainwater recirculation system for the urban gardens | x |
| Didactic area with courses on the energy theme | x |
| Courses about Eco-Design | x |
| Mini wind turbines | x |
| Refreshments in the parks | x |
| Urban gardens | x |
| Facilitated access to parks for elderly or disabled people | x |
| Multifunctional centre with high energy efficiency | x |
| Free surgery | x |
| Car parking near the metro station | x |
| New bowling club | x |
| Video surveillance | x |

The results show unequivocal conclusions:

- The level of degradation was judged insufficient by 77% of the sample;
- Social aggregation activities were judged insufficient by more than 70% of the sample;
- The connection with the world of work was judged insufficient by 94% of the sample;

- The possibility of installing renewable resources was rated positively by more than 80% of the sample as regards photovoltaic panels, while the mini turbines were judged unwelcome by 82% of the sample;
- Having been deemed insufficient by more than 80% of the sample to maintain green areas, its possible requalification was deemed positive by more than 60% of the sample;
- The possibility of creating new aggregation points (such as a multifunctional centre) was judged positive by more than 80% of the sample

### 4.6.4 Planning of Strategies

To solve problems exposed by the survey, different interventions are proposed:

1. Structural Interventions: aimed at the construction of the structures in which the multifunctional centre is carried out (Table 69);
2. Plant Interventions: aimed at equipping the redeveloped area with performing systems (Table 70);
3. Socio-Technological Interventions: aimed at the implementation of technologically innovative services to encourage social aggregation (Table 71).

Table 69: Structural characteristics.

| **Typology** | **Alternatives** | **Trasmittance [W/K*m²]** |
|---|---|---|
| Wall stratigraphy | 1. Frame X-Lam;<br>2. Normablock;<br>3. Aerogel;<br>4. Rock wool; | 1. 0,129;<br>2. 0,149;<br>3. 0,273;<br>4. 0,149 |
| Roof | 1. Frame X-Lam;<br>2. Rock wool; | 1. 0,13;<br>2. 0,182 |
| Floor | • Wood | • 0,182 |
| Glass surfaces | 1. Double low-emission glasses with PVC frames and argon;<br>2. Double low-emission glass with aluminised wood frames and argon;<br>3. Triple low-emission glasses with PVC frames and argon; | 1. 2,419;<br>2. 2,34;<br>3. 1,956; |

| | | |
|---|---|---|
| | 4. Triple low-emission glass with aluminised wood frames and argon; | 4. 1,877 |
| Interior finishes | • Airlite | • 0,077 |

Table 70: Energy system strategies

| **Plant Interventions** | |
|---|---|
| ***Typology*** | ***Alternatives*** |
| Photovoltaic panels | 1. Double-sided modules;<br>2. Modules with integrated power optimizers; |
| Storage | • Electrochemical batteries; |
| Heating and Cooling System | • Heat pumps external to the structures that feed the internal fan coils; |
| Rainwater Recirculation System | • Made up of conveyor, collection and distribution systems; |
| Illumination System | • LED light sources accompanied by automatic dimming;<br>• Solar brick;<br>• Mobile shading systems; |

Table 71: Social strategies

| **Socio-Technological Interventions** | |
|---|---|
| ***Typology*** | ***Alternatives*** |
| Perimeter video surveillance | Made up of video cameras equipped with own photovoltaic and storage; |
| Outdoor gym | Powered by the kinetic energy of users; |
| Wi-Fi Zone | Tor Bella Monaca is one of the few areas in Rome without free hot spots; |
| Urban gardens | Aims for social integration and cohesion between urban and natural dimensions |
| Recovery of the Roman Villa | Restoration of the remains present to create a historical route; |
| Smart Benches | Powered by own photovoltaic and storage; |
| Automatic watering | Intended for both urban gardens and the turf of the park; |
| Smart Parking | Through the images captured by three video cameras, the final users will see the availability of places on their smart phones; |
| Permanent charging stations for electric vehicles | For charging both low and high-power electric vehicles. |

Since the area considered, according to the Catasto di Roma" as "public green and public services of a global level", the 5% of the total area is buildable, about 3269,125 m$^2$. Given the large area available, the construction of a multifunctional centre is proposed, which is divided into different areas:

- Didactic area: aimed at teaching for students in front of high school and professional courses;
- Refreshment area: by creating a meeting point, such as a bar and restaurants.
- Rooms for infancy and childhood: the neighbourhood is densely populated by low-income families (more than 70%);
- Rooms for elderly people: space for educational and social activities;

Moreover, other outdoor activities will be located inside this area, dedicated to:

- Relax area: equipped with smart benches for recharging electrical appliances;
- Urban gardens: enslaved by the rainwater recovery system;
- Outdoor gym: self-sufficient thanks to the revolutionary Green Heart technology;
- A new path through the Roman Villa;
- Games area: in front of the playroom for young people;
- Parking: recovering the area located at the main entrance.

### 4.6.5 Simulation strategies

Thanks to the Matlab/Simulink simulation software, it was possible to create a model consisting of various sub-models, listed below.

- Thermal model

Using the data of the structural components stratigraphy's, the thermal behaviour of the various structures was analysed separately, separating the summer regime from the winter one. Climate data used for the simulation are extracted from the nearest measuring station of ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale). Regarding the thermal loads of the envelopes, it has been considered also the presence of thermal bridge and infiltrations. Finally, internal gains are calculated with concerning the presence of people, electric utilities and solar component [147]. The usefulness of this step lies in the possibility of obtaining values for sizing the heating and cooling system, but also to understand which is the best of the structural alternatives. The results of the thermal model show the high peaks of each structure; starting from the summer ones, the sizing of both the external heat pumps and the internal fan-coils were carried out for each structure, considering the load variation imposed by switching the structural alternatives. This must be done before modelling the electric one, as it constitutes a load [148];

- Electric Model

Among the various electrical utilities, lighting can be divided into two macro areas: the indoor (for the four structures) and the outdoor (for the park and parking). Thanks to the 3D Dialux design software, starting from the results of the Flux Method [149], it was possible to size the sources by defining the climatic conditions and to propose their automatic dimming by studying the interaction with natural light. Finally a model was created based on the data of the various users, divided by structure, by season, by time band (having the dimming valid in this interval) and considering the alternatives of the structural elements;

- Sizing of photovoltaic system and storage

For the photovoltaic panels it was done using data of the electric model, to cover all the energy needs; both the double-sided modules and those with integrated optimizers, were dimensioned in parallel. For the storage, an electrochemical one was studied for those loads that consume energy during the night, when the plant doesn’t produce, but which, in any case, fall within the energy sizing of the photovoltaic field, avoiding the introduction into the network of the daytime energy surplus produced;

- Sizing of rainwater recirculation system

This alternative has been analysed, using as a rainwater collection surface. The playroom for infancy and childhood are excluded from the sizing of the photovoltaic system;

- Analysis of socio-technological interventions

This strategy doesn’t have a consistent impact or advantage to be observed, because they implement a service that is absent today. Therefore, to evaluate their effectiveness, they were compared with similar technologies to calculate the economic savings throughout their life cycle, the net of the initial investment difference.

### 4.6.6 Performance Indicators

The proposed interventions can be described through the performance indicators which are useful to compare different solutions and evaluate their influence on the final asset [11,22]. The indicators chosen for this analysis are reported below (Table 72).

Table 72: Performance Indicators.

| **Axe** | **PI** | **Formula** | **Unit** |
|---|---|---|---|
| EN | Reduction of energy consumption compared to the base case | Base case energy - Energy intervention | kWh/yr |
| | Production of energy from renewable sources | $Area*h_{eq}*\eta_{BOS}$ | kWh/yr |
| | Energy destined for self-consumption by renewable sources | Total energy produced - Energy fed into the grid | kWh/yr |
| ENV | Reduction of emissions of $CO_2$ | PFR*0,32678 | kg/yr |
| | Reduction of emissions of $CO_2$ on the lifespan | RC*Lifespan | kg |
| MOB | Parking facilities served | Number of cars | / |
| LIV | Technological Services | Covered are | $m^2$ |
| | Safety | Covered are | $m^2$ |
| | Rating | Rating > 4 in the survey | / |
| EC | Initial investment | $C_{INV}+C_{LABOR}$ | € |
| | Economic savings from the production of renewable energy | $(PFR-EA)*C_{kWhGRID} + EA*C_{kWhSELPROD.}$ | €/yr |
| | Economic income compared to the base case | $(RECB*C_{kWh} - \|INV_{BASECASE} - INV_{INTERVENTIONS}\|) / Lifespan$ | €/yr |

A couple of considerations could be made referring to the table above to clarify some points.

- Regarding the structural elements (roof, wall, slabs and so on) and the plant energy systems, author defined a "base case" a case following the normative limitations or use a comparable technology. This was necessary in order to compare the proposed alternative solutions with a comparable base case.
- Prices and costs of the solutions are referred to commercial catalogue of 2019. Similarly, the life span of each strategy was found on the respective technical schedules.
- The value of RC was calculated following a parameters elaborated by ISPRA. It measured the kg of $CO_2$ saving per each $KWh_{el}$.
- Prices of the kWh bought by the consumers are established following the TERNA guidelines.

The standardization and weighting process of those indicators is taken from the work of [150]. Following the author described briefly all the steps of this procedure, highlighting a specific modification applied to the scaling phase.

**Standardization**: the "distance to mean method" was used as exposed in the QIMM approach.

**Scaling**: a modification on the range of the scaling process was done by the author to done to avoid the negative values, obtained especially for a group of strategies. A different evaluation was therefore assigned to the ranges between 0 and 10, not between -5 and 5. In this way, final results are more homogenous and coherent.

**Correction Factor**: this parameter was assigned as usual, a value of 1 if the indicator represent a positive impact and a value of -1 if not. Regarding the indicators exposed in Table 72, only the Investment one obtained the value of -1.

**Economic and Time feasibility**: to the various indicators considered, two other PIs must be added, which describe the economic and temporal feasibility; these will be normalized to obtain a value between 0 (worst case) and 1 (best case).

## 4.7 Results and discussion

### ➢ Thermal model results

Regarding the thermal model results, Table 73 below reported the worst and best case obtained for each alternative construction components, considering the summer thermal peaks. As showed in Table 73, aerogel has got a summer peak higher than 1000 kWt compared to the X-Lam and over 600 kWt compared to the other two alternatives. On the other hand, the triple glass solution obtained a higher savings respect to the double one (2100 kWt). Finally, regarding the frames, the difference between those alternatives is less than 50 kWt.

Table 73: Results of the thermal model.

| **Thermal Model Results** | | |
|---|---|---|
| **Typology** | **Best Case** | **Worst Case** |
| Wall stratigraphy | Frame X-Lam | Aerogel |
| Glass surfaces | Triple low emission; | Double low emission; |
| Frames | Aluminised wood | PVC |

### ➢ Electric model

Considering a distinction of the electrical loads in three categories, it is possible to define their annual consumption (Table 74):

- Loads of the structures: considering all the possible structural variations;
- Constant loads of the park;
- Non-constant loads of the park.

Table 74: Results of the electric model

| **Annual electrical consumption [kWh/yr]** | **Options** | | | |
|---|---|---|---|---|
| | ***X-Lam-Double Glasses.*** | ***X-Lam-Triple Glasses.*** | ***Rock wool-Double Glasses.*** | ***Rock wool-Triple Glasses.*** |
| Loads of structures | 17190 | 16753 | 18211 | 17730 |
| Constant loads of the park | 56180 | | | |
| Non-constant loads of the park | 51228 | | | |

## ➢ Photovoltaic and storage system

Considering the four structural alternatives (Table 69), the peak (kWs) necessary to satisfy the total electrical requirements oscillate between 88.09 kWp and 89.21 kWp. Starting from a common value of 90 kWp (the values found are however the result of simulations), the two alternatives proposed were compared with a monocrystalline photovoltaic module: there is a saving, in term of modules, of 86 units for the double-sided modules and 15 units for modules with optimizers. Consequently, the sizing of the system was carried out (arrangement of the modules and inverters) by considering the available areas separately, without the infancy's and childhood's playroom. Finally, the storage system requires 9.47 kAh.

## ➢ Rainwater Recirculation system

They were sized thanks thank to the model. The conveying systems therefore obtained a the length of 80 m. Regarding the pumps, a prevalence of 138 m is required, for a total of three units, equipped with an integrated electronic card for automatic start and stop. Finally, three underground tanks of four m$^3$ in plastic material, preferring a slight under sizing which favours the natural overflow of water.

## ➢ Socio-Technological Interventions

The simulation model shows the following results (Table 75).

Table 75: Results of the socio-technological model.

| **Intervention** | **Saving** | **Alternative** |
|---|---|---|
| Smart Parking | 19991 €/lifespan | Sensors and control unit |
| Video surveillance | 15015 €/lifespan | Video cameras without photovoltaic system |
| Gym Green Heart | 7408 €/lifespan | Tools attached to the power supply |
| Smart Benches | 2150 €/lifespan | Benches without recharge |
| Charging stations | 11270 €/year | No charging stations |

### 4.7.1 Final rakings

The final ranking of the interventions considered is shown in Table 76, in which the double-sided modules obtained the higher score and the urban gardens the lower. Analysing in detail the ranking of priority obtained, it is possible to observe a clear separation between the types of strategies, since in the first places there are the plant interventions, after the socio-technological ones and finally the structural ones. This issue could be related to the transversal influence obtained by energy system solutions. On the other hand, structural strategies had a low impact on the rest of the smart axis, explaining their worst position inside the ranking.

Table 76: Final smart ranking.

| **Global ranking** | |
|---|---|
| 70,7 | Double-sided modules |
| 66,7 | Modules with integrated power optimizers |
| 59 | Solar Brick |
| 46 | Smart Parking |
| 44,8 | LED with Dimming |
| 38 | Video surveillance |
| 37,8 | Cooling and heating system |
| 35,8 | Storage system |
| 31 | Recharge station |
| 28 | Wi-Fi |
| 27 | Gym |
| 18,9 | Mobile shading systems |
| 16,8 | Recovery of roman villa |
| 16 | Smart Benches |
| 15,9 | Triple low-emissivity glass with aluminised wood frames and argon |
| 15,8 | Triple low-emissivity glass with PVC frames and argon |
| 14,9 | Rainwater recirculation system |
| 13,8 | Double low-emissivity glass with aluminised wood frames and argon |
| 12,8 | Triple low-emissivity glass with PVC frames and argon |
| 12 | Automatic irrigation of turf |
| 11 | Automatic irrigation of urban gardens |
| 8,6 | Wall stratigraphy with X-Lam frame |
| 7,3 | Wall stratigraphy with rock wool /Normablock |
| 7,2 | Roof with X-Lam |
| 5,1 | Roof with rock wool/Normablock |
| 4,3 | Floor |
| 0,7 | Urban gardens |

This separation has led to the elaboration of partial rankings (Tables 77, 78, 79), distinguished by category of intervention, useful for evaluating in various cases (such as for example the type of photovoltaic modules or the type of roof) which is the most effective alternative.

Table 77: Smart ranking of the Structural strategies.

| **Ranking of Structural Interventions** | |
|---|---|
| 15,9 | Triple low-emission glass with aluminised wood frames and argon |
| 15,8 | Triple low-emission glass with PVC frames and argon |
| 13,8 | Double low-emission glass with aluminised wood frames and argon |
| 12,8 | Double low-emission glass with PVC frames and argon |
| 8,6 | Wall stratigraphy with X-Lam frame |
| 7,3 | Roof with rock wool |
| 7,3 | Roof with Normablock |
| 7,2 | Roof with X-Lam |
| 5,1 | Roof with rock wool/Normablock |
| 4,3 | Floor |

Table 78: Smart ranking of the Plant strategies.

| **Ranking of Plant Interventions** | |
|---|---|
| 70,7 | Double-sided modules |
| 66,7 | Modules with integrated power optimizers |
| 59 | Solar Brick |
| 44,8 | Dimming-LED |
| 37,8 | Cooling and heating |
| 35,8 | Storage system |
| 18,9 | Mobile shading systems |
| 14,9 | Rainwater recirculation system |

Table 79: Smart ranking of the Socio-Technological strategies.

| **Ranking of Socio-Technological Interventions** | |
|---|---|
| 45,9 | Smart Parking |
| 37,9 | Video surveillance |
| 30,9 | Recharge station |
| 27,9 | Wi-Fi |

| | |
|---|---|
| 26,9 | Gym Green Heart |
| 16,8 | Recovery of roman villa |
| 15,9 | Smart Benches |
| 11,9 | Automatic irrigation of turf |
| 10,9 | Automatic irrigation of urban gardens |
| 0,7 | Urban gardens |

Partial rankings are useful to understand deeply the priority inside these macro-areas. Regarding Table X, the best solution is the use of Triple low-emissivity glass with aluminised wood frames and argon instead the double ones; the X-LAM stratigraphy for the new buildings obtained a good score, is the best solution compared to the wall constructions ones. As aforementioned, double sided-modules had a consistent impact on different smart axes, obtained a higher score (Table XI). Finally, the smart parking development is the best strategies for the Socio-Technological solutions (Table XII), underlining its importance for the green area and also for the neighbourhood.

## 4.8 Conclusions

The following work aimed to define a smart planning model for the suburbs of cities, through the construction of a simulation model and through the application of a smart methodology for the strategies prioritization.

The role of the stakeholders was the fundamental key for the definition of the urban and social renewal proposals. However, the use of a methodology, that can guide the choice of those interventions that obtained a greater impact for the smart axes, is still an essential issue. Furthermore, through the model developed with Simulink, it was possible to study the interventions and quantify them in energy and economic terms.

The smart assessment was done using performance indicators that allowed the quantification of the impacts of even purely social strategies, which are difficult to manage and unfortunately remain in the background. Thanks to these tools, it was possible to study the redevelopment of a green area in Tor Bella Monaca, by building an efficient multifunctional centre both from an energy and social point of view.

Future developments foresee the application of this model to different realities of urban suburbs, in order to test and implement both the model created and the proposed QIMM approach.

# CONCLUSION

This thesis presents the evolution of a qualitative Smart planning methodology into a quantitative one for applying the Smart model to different urban realities. The IMM approach was therefore integrated and adapted to a universities campus, keeping the focus on the CIs and their standardization and weighting process. Successively, this method is completely transformed into a quantitative and ex-post approach, named QIMM, to overcome the subjectivity that affects a qualitative evaluation. The principal aim of this work indeed meets the needs highlighted in literature in the development of Smart City projects: quantitative and complete planning models are required to identify objectively the problems of the cities. The exposed method could be therefore a useful instrument for decision-makers and planners for the identification of the most performing Smart strategies and the quantification of their impacts on the territorial levels.

Starting from the qualitative Incidence Matrix Method (IMM), in Chapter 1 it is synthesized the integrations made by the author. Specific standardization approaches are chosen for the performances indicators elaboration. In parallel, a set of CIs was developed for the university's campus able to describe all the aspects from the academic perspective to the mobility ones. The smart axis proposed also represent the essential fields that have to be investigated for the smart concept application. Then, those CIs indicators and methods for data standardization and aggregation have been applied to the engineering faculty of La Sapienza University, San Pietro in Vincoli (Rome) chosen as a case study.
The smart ranking is finally drafted, highlighted the urgent call of the complex to be refurbishment in term of energy aspects due to the old envelope and obsolete energy systems of the Campus. Conversely, the smart axes Living the Campus obtained the best score, highlighting the variety and efficiency of the academic services. A set of solutions were proposed for all the smart axes and they were analyzed through the qualitative Incidence Matrix, wherein a smart winner solution is identified for each field. Simulations are carried out for the energy axes, the worst one, to concretely provide the expected benefits. An open-source software called Grasshopper/Archism, was chosen for this scope, thanks to its flexibility in the 3D modelling.

Results showed that the application of the two strategies, the new window fixtures and the shading placement, provided a sensible reduction of the Operative Temperature (OP) and guaranteed the lighting indoor comfort.

In Chapter 2, the evolution of the IMM approach into a quantitative and ex-post method was deeply described. According to this, this work aims to expose and validate the QIMM planning approach through the comparison with the Hybrid AHP method, another decision-making method presented in the literature, and the application of these two models to two real case studies. Those case studies belong to two different territorial levels: a district and a building, demonstrating the flexibility of the two approaches to be adapted to several urban contexts. In general, results show that the two methods, despite their differences, gave the same outputs regarding the best and worst-performing solutions.

In detail, for the Sicilian case study, stakeholders' vote included in the Hybrid AHP method has a relevant impact on the score of a few actions, considerably altering their positions in the rank. In line whit this, the ranks of the two methods are not completely aligned concerning the intermediate positions. However, when the stakeholders' opinion of the Hybrid AHP and the additional cost and time scores in the QIMM are excluded from the analysis, the ranks come out to be very similar. This fact demonstrated that the normalization process of the two methods provided comparable results despite their considerable differences. Conversely, the Baleani case study shows aligned results with the two methods, mainly because the stakeholders' vote is not included. Summing up, results showed some positive aspects of the QIMM such as the reliability and the easiness of normalization process, the balanced attribution of the scores in the scaling scheme, the objectivity of the prioritization process by applying quantitative parameters (correction factor and economic and time weights) and the scalability of the method to different territorial contexts. Finally, results demonstrated that the stakeholders' opinion in the Hybrid AHP model has a clear impact on the final ranking. High importance, therefore, is given to them but it is essential to avoid results too subjectively. In line with this, future developments would overcome some limits of the QIMM approach with regards to the stakeholder's opinion. At present, their voices are not taken into account and it would be useful to include them in the process through weighted factors.

Chapter 3 presents a resilient energy microgrid, based on CHP biomass plant and a district heat networks (DHN), applied to a real case study, located in the mountain Italian region. In detail, six communities are connected through the DHN that is feed by biomass CHP plants, using the local woodchips. Moreover, to face failures and blackout of the energy plants, two resilient energy systems scenarios were developed. Knowing the power of resilience in the communities, this two configurations of this energy microgrid are deeply analysed (Case A and Case B), increasing the size of the CHP biomass plant and the CHP and boilers, respectively. The MATLAB/Simulink is chosen for creating the entire dynamic energy/environmental system. The energy microgrid was developed starting from the Sersale village, calculating its thermal and electrical requirements and the final energy system size. In general, results highlighted the essential role of the auxiliary boiler that ensures the thermal needs, attested to 46 MW. Regarding case A, the best scenarios are 2, 4, and 6 since the involved communities showed similar heat generation capacity also in the case all the plants were on. The worst scenario is related to the Sersale's energy generation plant shutdown, being the largest village. Regarding the case B, it showed a similar trend for all the scenarios compared to case A but slightly reduced, thanks to the increased capacity of auxiliary boilers.

The application of QIMM method to the six scenarios (Base, Base1, ResA, ResA1, ResB and ResB1), simulated in the MATLAB/Simulink model, provided a final smart ranking. In details, scenario ResB gained the highest scores in terms of energy, environmental and economic benefits, as smart and resilient indicators pointed out. The worst scenario was the Base case, presenting some weakness in term of energy and economic benefits compared to the other scenarios. Furthermore, the ranking without the resilient indicators showed similar results, maintaining the worst and best strategies in the rank. According to this, the impact of the resilient indicators, elaborated in this chapter, is well balanced, providing the right weight to all the scenarios.

Keeping in mind, this is the first step of this study to include the resilience theme, the next aim is to expand its significance and influence in the QIMM process.

In Chapter 4, a sustainable suburb was modelled. This suburb, named Tor Bell Monaca, has been designed with sustainable strategies from the social, energy and economy points of view and it is located in Rome. According to the methodology described in Chapter 2, each phase of the method was applied, starting from the preliminary planning. Moreover, the role of the stakeholders was included in the method to fill the gap evidenced in the QIMM methodology. Stakeholder's opinion was essential to define the smart project, a multifunctional centre. Then, a list of solutions was proposed, from energy to social view. To prioritize them, the QIMM approach demonstrated its relevance as a reliable smart planning tool. Furthermore, through the model developed with MATLAB/Simulink, it was possible to study the interventions and quantify them in energy and economic terms. The final smart assessment was developed thanks to the performance indicators that allowed the quantification of the impacts of even social strategies, which are difficult to manage.

The present research aims to fill the gap with the previous works exposed in literature, providing another important piece of this complicate puzzle for developing a complete smart planning model. The QIMM methodology requires further improvements, especially for involving the resilience theme inside the smart process.
Moreover, different comprehensive ways of including the stakeholder's opinion are necessary for this smart approach. To become an easy and useful tool for designers and politicians, this methodology could be transformed into a digital platform, wherein users are allowed to create their smart projects and obtained concrete results for each local contexts.

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(Chpater 3) Economic and financial indicators of the base case scenario (with purchased woodchips) are reported below as a reference (data extracted from the work of [137] and elaborated in Matlab/Simulink).

Table i: Specific cost of the energy source

| | | |
|---|---|---|
| Electric energy | 0.22 | €/kWh |
| Firewood | 13 | €/q |
| LHV firewood | 4 | kWh/kg |
| Natural gas | 0.8 | euro/m$^3$ |
| LHV natural gas | 9.94 | kWh/m$^3$ |
| Woodchips | 0.03 | euro/kg |
| LHV woodchips | 3.4 | kWh/kg |
| Maintenance costs for gas boiler | 132.5 | euro/anno |

Table ii: Investment costs and running cost

| | | | **Sersale** | **Cerva** | **Petronà** | **Andali** | **Zagarise** | **Magisano** | **TOTAL** |
|---|---|---|---|---|---|---|---|---|---|
| Cogenerator | Investment | € | 2000000 | 650000 | 1500000 | 650000 | 1000000 | 650000 | 6450000 |
| | TOTAL COST OF INVESTMENT | € | 2000000 | 650000 | 1500000 | 650000 | 1000000 | 650000 | 6450000 |
| | O&M | €/year | 46375 | 15071 | 34783 | 15071 | 23184 | 15071 | 149555 |
| | Fuel | €/year | 446294 | 145059 | 334765 | 145059 | 223147 | 145059 | 1439382 |
| | TOTAL RUNNING COSTS | €/year | 492669 | 160130 | 369548 | 160130 | 246331 | 160130 | 1588937 |
| Boiler | Investment | € | 1530000 | 289000 | 680000 | 272000 | 476000 | 263500 | 3510500 |
| | TOTAL COST OF INVESTMENT | € | 1530000 | 289000 | 680000 | 272000 | 476000 | 263500 | 3510500 |
| | O&M | €/year | 88620 | 16737 | 39390 | 15753 | 27570 | 14769 | 202839 |
| | Fuel | €/year | 306618 | 5771 | 136235 | 54512 | 95382 | 51106 | 649624 |
| | TOTAL RUNNING COSTS | €/year | 395238 | 22508 | 175625 | 70265 | 122952 | 65875 | 852463 |
| Network tank | Investment | € | 160000 | 56000 | 120000 | 56000 | 80000 | 56000 | 528000 |
| Distribution network | Pipes | € | 280854 | 67122 | 156870 | 65351 | 106542 | 63580 | 740318 |
| | Users substations | € | 343266 | 82038 | 191730 | 79873 | 130218 | 77708 | 904834 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Auxiliaries | € | 270452 | 64636 | 151060 | 62930 | 102596 | 61225 | 712899 |
| | TOTAL COST OF INVESTMENT | € | 894572 | 213796 | 499660 | 208154 | 339356 | 202513 | 2358051 |
| | Pumping | €/year | 83216 | 19888 | 46480 | 19363 | 31568 | 18838 | 219354 |
| | O&M | €/year | 113642 | 27160 | 63474 | 26443 | 43110 | 25726 | 299555 |
| | TOTAL RUNNING COSTS | €/year | 196858 | 47048 | 109954 | 45806 | 74678 | 44565 | 518908 |
| Fees for experts | | € | 458457 | 120880 | 279966 | 118615 | 189536 | 117201 | 1284655 |
| Salaries for workers | | €/year | 144000 | 46800 | 108000 | 46800 | 72000 | 46800 | 464400 |
| TOTAL INVESTMENT | | € | 5043029 | 1329676 | 3079626 | 1304770 | 2084892 | 1289214 | 14131206 |
| TOTAL RUNNING COSTS | | €/year | 1228765 | 276485 | 763127 | 323001 | 515961 | 317369 | 3424708 |

The Long Run Marginal Costs for the production of a unit of electricity and a unit of thermal energy by means of the energy generation systems under study are summarized in the following tables. Note that also in this case all the costs items are explained in Appendix 3. The analysis considers a technical life of the plants of 30 years and an actualization factor of 4% (WACC 1%).

Table iii: Calculation of marginal cost for purchased woodchip

| **BASE** | | **Sersale** | **Cerva** | **Petronà** | **Andali** | **Zagarise** | **Magisano** |
|---|---|---|---|---|---|---|---|
| Electric energy by CHP | €/kWh | 0.0894 | 0.0892 | 0.0892 | 0.0892 | 0.0892 | 0.0892 |
| Thermal energy by DH | €/kWh | 0.0291 | 0.0312 | 0.0311 | 0.0314 | 0.0309 | 0.0317 |

Table iv: Total revenues

| | **Revenues [€]** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Sersale** | **Cerva** | **Petronà** | **Andali** | **Zagarise** | **Magisano** | **TOTAL** |
| Thermal energy sale to | 1513000 | 387800 | 903400 | 380000 | 609700 | 373200 | 4167100 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| customers | | | | | | | |
| Electric energy sale to customers | 412100 | 83440 | 231500 | 101600 | 116100 | 95370 | 1040110 |
| Electric energy sale to GSE | 113800 | 68560 | 133400 | 57130 | 113200 | 60480 | 546570 |
| Total | 2038900 | 539800 | 1268300 | 538730 | 839000 | 529050 | 5753780 |

Table v: Total financial forecast

| | | **Sersale** | **Cerva** | **Petronà** | **Andali** | **Zagarise** | **Magisano** | **TOTAL** |
|---|---|---|---|---|---|---|---|---|
| Investment | € | 5043029 | 1329676 | 3079626 | 1304770 | 2084892 | 1289214 | 14131206 |
| Technical life | years | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| Revenues | €/year | 2038900 | 539800 | 1268300 | 538730 | 839000 | 529050 | 5753780 |
| Annual costs | €/year | 1228765 | 276485 | 763127 | 323001 | 515961 | 317369 | 3424708 |