POLITECNICO DI TORINO

Master of Science course in Energy and Nuclear Engineering

Master of Science Thesis

# TOWARDS SMART BUILDINGS. IS THE SMART READINESS INDICATOR AN EFFECTIVE TOOL?

## The Energy Center building of Turin as case study to explore the challenges of the smart building revolution


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*A mamma e papà*

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# Abstract

As clearly declared by the European Union (EU) in the framework of the EU climate actions and of the long-term strategies up to 2050, the building sector has an essential role in achieving the advocated energy transition. In order to reach the energy and emission reductions goals, actions are needed to increase energy savings and efficiency at building and system level, as well as to improve occupants' wellbeing and satisfaction. To do this, a new multi-disciplinary paradigm is essential, able to tackle all the building-system-occupant challenges and interactions. The objective of the work is to explore different levels of knowledge and detail of a building, in order to better identify its points of strength and weakness, but also to compare the instruments used to measure the buildings performance and the performance itself.

In this context, the choice of the case study is essential, and the thesis focused on the complex building of the Energy Center (EC) at Politecnico di Torino. The reason behind the conceptualization of the Energy Center was the idea to create an innovative and stimulating environment able to put in contact several actors of the energy, environmental and political fields. This combination of multi-disciplinary expertise and research areas represents the main objective of the Energy Center, idea that was exploited since its initial building design and construction phase, which represented the result of the application of innovative techniques and of multi-disciplinary researches to guarantee high levels of energy savings, smartness, comfort and innovation. The project was based on the idea to create a multi-energy environment, integrating different energy production systems and resources, among which of course renewable technologies, to be used also for further research. In addition, an advanced monitoring system and control was developed in order to achieve an efficient management of the entire building.

Starting from this background, the thesis aimed to study and assess the EC energy behaviour, strengthen on three diverse levels of knowledge, increasingly more detailed and deeper. First, the building was analysed through the calculation of a unique indicator (the Smart Readiness Indicator, SRI), able to synthesize the overall building technological features and readiness to smartness, in terms of capability to easily respond and adapt to both energy systems and grid and occupants' needs, through the use of a multi-criteria assessment method. Secondly, an analysis based on the real building operation was performed, assessing the building energy behaviour by exploiting the available monitored data, in order to capture possible rooms for improvement to achieve an efficient energy management and control. Finally, the thesis

considered the development of an energy-dynamic model, using the EnergyPlus simulation tool; after calibrating the model according to the building project data, through the energy simulations it was possible to explore different scenarios of energy management and control, to evaluate to what extent these actions could have an impact on the overall SRI calculation and assessment. The analysis allowed to deepen and comment on the efficacy of the SRI of being a real tool of building behaviour assessment, able to link the indicator itself with the real energy needs of the building,  and to understand if and how the indicator is sensible to building energy needs variations.

# Nomenclature

AHU – Air Handling Unit

ARPA – Agenzia Regionale Protezione Ambiente

BACS – Building Automation and Control System

BEM – Building Energy Modeling

BPIE – Building Performance Institute Europe

BREEAM - Building Research Establishment Environmental Assessment Method

CEPS – Centre for European Policy Studies

DR – Demand Response

DSM – Demand Side Management

E3G - Third Generation Environmentalism

EBC – European Builders Confederation

ECF - European Climate Foundation

EHPA - European Heat Pump Association

EPC – Energy Performance Certificate

eu.bac - European Building Automation and Controls Association

EU-ASE – European Alliance to Save Energy

EuroACE - European Alliance of Companies for Energy Efficiency in Buildings

EuropeOn – The European Association for Electrical Contractors

ICT – Information and Communication Technologies

IEA – International Energy Agency

INECP – Integrated National Energy and Climate Plan

INRiM – Istituto Nazionale di Ricerca Metrologica

IT – Information Technology

LEED – Leadership in Energy and Environmental Design

LTRS – Long-Term Renovation Strategy

MCA – Multi-Criteria Analysis

RES – Renewable Energy Sources

TBS – Technical Building System

VITO – Vision on Technologies (Flanders)

# Figures

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# 1. How to describe, evaluate, improve the built environment pushing towards the smart revolution?

***Context and possibilities, from the objectives of the European Green Deal to the key requirements for smart building solutions***

Talking about the built environment today does not mean talking about the sole building. It is completely the opposite. In the building sector, a strong revolution has started, considering the strategic role of the built environment in facing and supporting the challenges of our future, regarding sustainability, digitalization, decarbonisation, circularity.

Buildings are in a transition phase [1]: from a centralised, fossil-fuel based and highly energy-consuming system, to a built environment more efficient, decentralised, consumer-focused and powered by renewable energy resources. It is a new concept of building, which can consume, produce, supply and store energy at the same time, becoming a new micro-energy hub.

## *1.1 Rethinking the future among challenges and possibilities, following the Energy Roadmap 2050*

Developing a timeline to put in evidence the most important events, actions, regulations and agreements involving the big issue of climate change and its consequences consists of a very challenging and ambitious objective; during the last decades several possibilities to act were taken into account but lots of them were not achieved or, in some cases, changed in time. The strongest certainty in this context is that the awareness about the problem and the need to adopt radical changes involving everything and everybody are rapidly increasing in the last period. Having clearly in mind that buildings represent a piece of the problem and of course a piece of its solution, and not for a little share, I chose as the starting point of this discussion "The roadmap for moving to a competitive low-carbon Europe in 2050" [2], published in 2011, but of course representing a milestone in the development of long-term and credible climate polices concerning European perspectives towards a more sustainable future. The main goal regards the GHG emission reduction by at least 80% by 2050 compared to 1990 levels. Of course, to ensure this cost-effective target, other two mid-term objectives were introduced: -40% for 2030 and -60% for 2040. In this framework the Energy Roadmap 2050 as support became essential [3], defining clearly that "only a new energy model will make our systems secure, competitive and sustainable in the long-run". In particular, the roadmap confirmed the feasibility from an economical point of view of the low-carbon goal, but there is the need of acting quickly, to define clearly the targets for the middle-terms and to achieve them, finally to act in a common market, the European one, in solidarity.


*Figure 1 - Means to reach the European goals according to the 2050 Energy Roadmap [3]*

As underlined by the figure above, achieving the energy security, sustainability and competitiveness in the long-term vision is of course the core of the roadmap, having clear in mind the need to develop a neutral framework in which the national, regional and local energy policies are not replaced but supported and improved. Among the analysed scenarios in the Energy Roadmap and the relative conclusions made, from the increasing role of electricity to the need of a strong rise in renewables, one of interest for this work regards the claimed responsibility for all. Since in 2011 it was underlined that "Higher energy efficiency in new and existing buildings is the key. Nearly Zero Energy Buildings should become the norm. Buildings – including home – could produce more energy than they use. Products and appliances will have to fulfil highest energy efficiency standards. [..] With smart meters and smart technologies such as home automation, consumers will have more influence on their own consumption patterns." And also, "In general, energy efficiency has to be included in a wide range of economic activities from, for example, IT system developments to standards for consumer appliances. The role of local organisation and cities will be much greater in the energy systems of the future." This is what I want to remark, being in line with the core of this thesis and the new vision of the problems and solutions regarding the energy transition mechanisms and their consequences; in other words, the new vision is involving each occupant, as occupant of a building in which he works or lives and as an occupant of the entire world itself. Moreover, in line with the focus of this work, there is another point of interest about the changes of the energy system, the one regarding the smart technologies, "an increasingly important feature of the required technology shifts is the use of information and communication technologies (ICT) in energy and transport and for smart urban applications. [...] The digital infrastructure that will make the grid smart will also require support at EU level by standardisation and research and development in ICT." [3].

Another key step is made by the Energy Union Strategy [4], published on 25 February 2015 as a key priority of Junker Commission (2014-2019), with the aim to create a union giving EU consumers - households and businesses - secure, sustainable, competitive and affordable energy, as expressed by fig. 2 in the next section.

Finally, to conclude this introduction to the themes and the context of analysis, of course there is the need to mention the Paris Agreement adopted by COP 21 in December 2015, that by limiting the global warming to well below 2°C and setting the limit to 1.5°C, represents a bridge between today's polices and climate neutrality before the end of the century.

## *1.2 Clean Energy Package and long-term strategies: implications at local, national, EU level of EPBD, EED, RED, Governance Regulation*

The new vision needs to be supported by legislations and future strategies to be implemented in the framework of the energy policy, at the local level but also at the global one. A strong push is given by the "Clean Energy Package", or better, "Clean energy for all Europeans package", an agreement discussed and signed by the European Commission in order to give a robust update to the energy policy framework of the European Union; it is an essential step forward the Energy Union Strategy of 2015. The Clean Energy Package is in fact based on the proposals of the Commission made known in November 2016, which carried to the definition of eight legislative acts; between May 2018 and May 2019, there was the political agreement by the Council and the European Parliament, so that the European countries had time to translate these directives into national legislation. These legislative acts, introducing to accelerate the transition towards a decarbonised system and to be in line with the EU's Paris Agreement commitments for reducing greenhouse emissions, are the followings:

- Energy Performance of Buildings Directive (EU) 2018/844;
- Renewable Energy Directive (EU) 2018/2001;
- Directive on Energy Efficiency (EU) 2018/2002;
- Regulation on the Governance of the Energy Union and Climate Action (EU) 2018/1999;
- Regulation on the internal market for electricity;
- Directive on common rules for the internal market for electricity;
- Regulation on risk-preparedness in the electricity sector;
- Regulation establishing a European Union Agency for the Cooperation of Energy Regulators.

Among these, the regulation EU 2018/1999 underlines the key dimensions of the Energy Union:

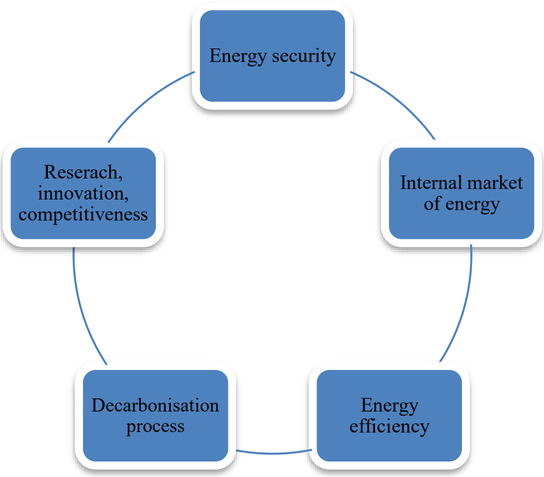


*Figure 2 - The key dimensions of the Energy Union; Regulation EU 2018/1999 [4]*

Having this general overview, it is clear that the process leading to the energy transition and a new awareness of the Member States towards innovative strategies is a challenge together for society, economy and environment. The most significant legislative action for the building sector is the Energy Performance of Building Directive, known as EPBD [5], adopted in 2002, recast in 2010 and amended in 2018. As underlined by a report of the Building Performance Institute of Europe [6] the core component of this Directive is given by the Long-Term Renovation Strategies; their overall goal is achieving a decarbonised building stock by the 2050, making also possible and effective the transition from existing buildings to Nearly-Zero Energy Buildings, whose definition is included in Article 2.2 of the EPBD. As published by the International Energy Agency (IEA) in the section related to the EU policy [7], "About 75% of buildings are energy inefficient and, depending on the Member State, only 0.4-1.2% of the stock is renovated each year." So, in this framework the need of an acceleration towards a cost-effective renovation of the building stock is evident, where this renovation "represents a win-win option for the EU economy as a whole". The Long-Term Renovation Strategies involves an overview of polices and actions to target the overall building stock, to stimulate a cost-effective deep renovation, to promote smart technologies and well-connected buildings and communities, improving at the same time skills and knowledge in the construction sector and the energy efficiency one. Moreover, there is the need to exploit evidence-based estimate of expected energy savings and benefits, involving the several macro-themes related to the built environment; comfort, health and safety are some of relevance. As underlined by an article on EU Policy section of REHVA website, about "Key new elements of the revised EPBD relating to HVAC sector", [8], the EPBD revision pushed for reinforcing the use of continuous electronic monitoring and building automation and control.

Having the general guidelines of the EPBD clearly in mind, the Member States have to define their Long-Term Strategies to be implemented directly at the national level; here the support of all the possible stakeholders involved and their field of interest has a strong relevance, considering the wide impact of the LTRS on the various sectors concerning energy, economy, environment, climate, urban development. In this context, the authorities, as suggested by the EPBD, have to develop and increase the mobilisation of investments, in terms of aggregating projects, public funds to leverage private investments, guiding investment in public building sector and, last but not least, advisory tools in order to achieve a more complete and detailed view on problems and solutions in terms of methods and practices to effectively enhance the performance of a building.

In the EPBD Article 8.10 and Annex I A is then introduced the Smart Readiness Indicator (SRI), as effective tool in order to evaluate and characterize a building according to its smartness, or better, its smart readiness; the European Commission is required to establish a rating scheme for the definition of the methodology to evaluate this indicator, which "should be used to measure the capacity of buildings to use information and communication technologies and electronic systems to adapt the operations of buildings to the needs of the occupants and the grid and to improve the energy efficiency and the overall performance of buildings". Testing the effectiveness of this proposed Smart Readiness Indicator is the main objective of this thesis work.

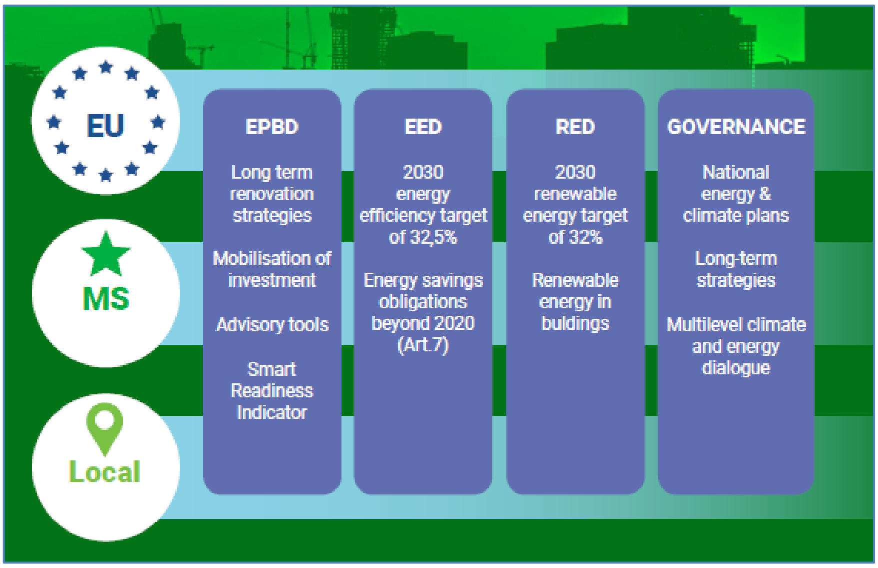


*Figure 3 - Core components of the Clean Energy Package relevant for building renovation policy; BPIE [6]*

To reassume the main measures and goals of the EPBD – which is the most interesting for the purpose of the thesis – as suggested and underlined on the European Commission official website, these are its main features:

- all the Member States must establish strong Long-Term Renovation Strategies to achieve the decarbonisation of the building stocks by 2050, with indicative milestones for 2030, 2040, 2050. The strategies should contribute to achieve the Integrated National Energy and Climate Plans (INECPs) energy efficiency targets;
- the EU countries must set cost-optimal minimum energy performance requirements for new and existing buildings, and to replace elements or adopt retrofit solutions;
- since 31 December 2018 all the new public buildings already need to be nZEBs, while all the new need to be nZEBs from 31 December 2020;
- EPCs must be issued in case of a sold or rented building and an establishment of inspection schemes for HVAC systems is required;
- EU and Member States must support electro-mobility by introducing minimum requirements for car parks and infrastructures for buildings;
- the Commission will introduce an optional scheme for rating the smartness of buildings;
- EU and Member States must promote smart technologies, also through requirements on the installation of building automation and control systems and on device that regulate temperature at room level;
- health and well-being of occupants is addressed, paying attention, among the others, to IAQ and ventilation;
- the Member States must list the financial measures to improve their building system at the national level.

The majority of these points will be taken into account in the discussion around the Smart Readiness Indicator and its definition; in other words, it can be seen also as a way to reassume the state-of-the-art of buildings from different points of view, giving the possibility to explore and think about new possible solutions and services in order to increase their performance, users' awareness and well-being, energy savings.

## *1.3 The European Green Deal in the priorities program 2019-2024*

Talking about the new projects and strategies of Europe, a “new entry” is the European Green Deal, in the priorities program 2019-2024; it represents a roadmap for Europe towards a new sustainable economy for the European countries, by investing in environmentally-friendly technologies, by decarbonising the energy sector, by ensuring also more efficient buildings. The starting point of this ambitious program has its basis in some primary information underlining the importance to develop big and great strategies in order to support the energy transition process for a sustainable future, in line with the Roadmap 2050:

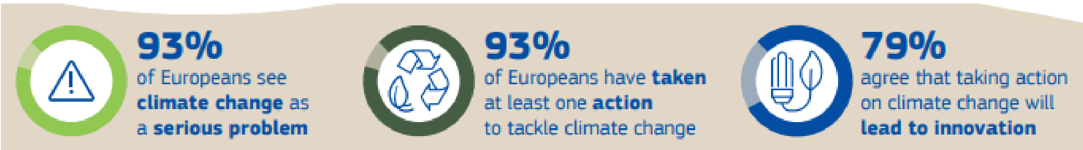


*Figure 4 - From the factsheet "What is the European Green Deal?"; EU Commission [9]*

In the factsheet mentioned above [9], the actual President of the European Commission, Ursula Von der Leyen, stressed how “The European Green Deal is our new growth strategy. It will help us cut emissions while creating jobs.” Moreover, “We propose a green and inclusive transition to help improve people’s well-being and secure a healthy planet for generations to come”, the Executive Vice-President, Frans Timmermans, added.


*Figure 5 - The main elements of the Green Deal; EU Commission [10]*

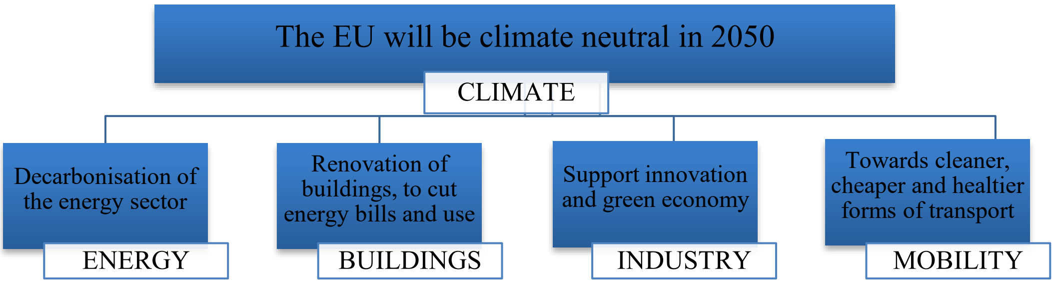


*Figure 6 – Adapted from "What will we do?", "What is the European Green Deal?" factsheet; EU Commission [9]*

Going deeper in "Building and renovating" targets, as explained in the related document [11], the design of buildings should be in line with the circular economy, the digitalization must be increased, the strict reinforcement of rules on energy performance of buildings is required. About the Green Deal, a Joint Statement was signed by the most important actors of the building sector: The Coalition for Energy Savings, Energy Cities, EuroACE, EU-ASE, EuropeOn, EBC, eu.bac, ECF, EHPA, smarten, SolarPower Europe, E3G. The document underlines the link between a better built environment and an improvement in citizens' well-being, also the need of better buildings to support the security of supply for all the European countries. It is essential translating this awareness in concrete actions, having already the possible solutions to overcome the issues related to energy transition; "high performance envelopes, energy efficient products and services, on-site renewables, demand response, energy storage facilities, and digitally enabled energy management systems are cost-effective and mature solutions". What it is required and missed up to now is an acceleration through significant investments facilitated by innovative financial mechanisms [12]; concrete strategies are proposed to the European Commission, to help in terms of policies and effective actions to be applied as soon as possible. Among them:

a) the need to develop a multi-level implementation platform for integrated building renovation strategies, using for instance the Climate Pact for this initiative;
b) the necessity to revamp blended financing mechanisms accessible to everyone, from citizens to energy managers;
c) the importance of raising awareness of the benefits coming from the improvements of building performance by the use of adequate and new tools;
d) the need to develop strategies overcoming decision-making fragmentation and able to adapt to the heterogeneity of buildings and their different purposes and priorities.

The point a) talks about the Climate Pact; it is important to say that the Commission proposed to lunch it in the last quarter of 2020 aiming to inform, inspire and foster cooperation between people and organisation ranging from national, regional and local authorities to businesses, unions, civil society organisations, educational institutions, research and innovation organisations, consumer groups, individuals. The project will build on and amplify the existing activities, trigger and embrace new ones, offering opportunities for collaborations [13].

Considering that each country must set and follow its own targets for the 2030 to reach the common goals of the European Union, according to the mechanism of governance developed by the Commission, Italy sent its Integrated National Energy and Climate Plan (INECP) for 2021-2030; simultaneously the activities for the implementation of the European Directives are at the national level are ongoing. In the document of the Italian Parliament, [14], the most important targets and strategies are summarised; in particular, there are considerations and comments related to the INECP developed and signed by the Ministry of Economic Development, Ministry of the Environment and Protection of Natural Resources and the Sea, Ministry of Infrastructure and Transport.

*Table 1 - Primary energy and climate objectives for 2020 and 2030, EU and Italy; INECP of Italy, December 2019 [15]*

| | 2020 objectives | | 2030 objectives | |
|---|---|---|---|---|
| | EU | ITALY | EU | ITALY (INECP) |
| **Renewable energies (RES)** | | | | |
| Share of energy from RES in the gross final consumption of energy | 20% | 17% | 32% | 30% |
| Share of energy from RES in the gross final consumption of energy in the transport sector | 10% | 10% | 14% | 22% |
| Share of energy from RES in the gross final consumption of energy for heating and cooling | | | +1.3% per year (indicative) | +1.3% per year (indicative) |
| **Energy efficiency** | | | | |
| Reduction in primary energy consumption compared to the PRIMES 2007 scenario | -20% | -24% | -32.5% (indicative) | -43% (indicative) |
| Final consumption savings as a result of obligatory energy efficiency systems | -1.5% per year (without transport sector) | -1.5% per year (without transport sector) | -0.8% per year (with transport sector) | -0.8% per year (with transport sector) |
| **Greenhouse gas emissions** | | | | |
| Reduction in GHG vs 2005 for all plants subject to ETS rules | -21% | | -43% | |
| Reduction in GHG vs 2005 for all non-ETS sectors | -10% | -13% | -30% | -33% |
| Overall reduction in greenhouse gases compared to 1990 levels | -20% | | -40% | |
| **Electricity interconnectedness** | | | | |
| Level of electricity interconnectedness | 10% | 8% | 15% | 10%[1] |
| Electricity interconnection capacity (MW) | | 9.285 | | 14.375 |

As reported in the table taken from the INECP sent to the European Commission, the most relevant targets of Italy can be found in the share of 30% of RES by 2030 in the final gross energy consumption, in a reduction of 43% of the primary energy consumption with respect to the PRIMES 2007 (the EU target was of -32.5%), in a GHG emissions reduction emphasized of the 3% with respect to the EU requirements [15]. Moreover, in the document of the Parliament aforementioned, it is underlined the commitment of the European Commission to better present the guidelines for the integration of smart technologies in our living environment during the current year (2020); it is evident that the digitalisation is a key feature to achieve the sustainable targets of the European Green Deal.

In the following lines, the timeline of the Green Deal is summed up, and some considerations need to be done in order to face the effectiveness of these ambitious strategies involving all the different sectors and to verify how the work is going on in terms of reached goals:

| | |
|---|---|
| 11 Dec 2019 | • Presentation of the European Green Deal |
| 14 Jan 2020 | • Presentation of the European Green Deal Investment Plan and the Just Transition Mechanism |
| 4 Mar 2020 | • Proposal of the European Climate Law to ensure a climate neutral Europe by 2050<br>• Public consultation on the European Climate Pact |
| 10 Mar 2020 | • Adoption of the European Industrial Strategy, a plan for a future-ready economy |
| 11 Mar 2020 | • Proposal of a Circular Economy Action Plan focusing on sustainable resource use |
| 20 May 2020 | • Presentation of the "Farm to fork" strategy to make food systems more sustainable<br>• Presentation of the EU Biodiversity Strategy for 2030 |
| 8 Jul 2020 | • Adoption of the EU strategies for energy system integration and hydrogen to pave the way towards a fully decarbonised, more efficient and interconnected energy sector |
| Summer 2020 | • Impact Assessment Plan to increase the EU 2030 Climate target |
| 2020 | • Strategy for smart sector integration<br>• *"Renovation wave" initiative for the building sector* |
| 2020 | • Evaluation and review of the Trans-European Network<br>• Energy Regulation |
| 2020 | • Strategy on offshore wind<br>• Lead markets initiative for climate neutral and circular products in energy intensive industrial sectors |

*Figure 7 - 2020 timeline for the European Green Deal; adapted from EU Commission website [16]*

Being the 2020 the current year, it is possible now verifying if and how the European countries are following the guidelines and the targets; "Europe didn't learn to consume energy in an efficient way yet" is the title of an article on Il Sole 24 ORE, [17]. The actual consumption of primary energy is higher than 4.9% with respect to the 2020 targets and higher than 22% with respect to the 2030 goals. For the final energy consumption, +3.2 % for the 2020 targets and +17% for the 2030. These data are referred to the 2018 consumption. So, the article mentioned above is referred to the period before the pandemic emergency started at the end of February involving all the European countries and the entire world. Talking about the reached goals and future objectives it is necessary to distinguish a pre-pandemic period and a post-pandemic one, especially if the subject is a climate neutral Europe by 2050 and all the choices to be done must fix this ambitious purpose. The Executive Vice-President Frans Timmermans said that "The European Green Deal must become the cornerstone of Europe's pandemic recovery. Rather than rebuilding the 20th-century economy, we must focus on spending stimulus money wisely and on preparing Europe for a competitive and inclusive 21st century, climate-neutral future."

In a document shared by CEPS – Centre for European Policy Studies – based in Brussels, it is underlined that the recovery measures need to be compatible with the global climate change and the European Green Deal priorities [18]. "The social and industrial dimensions of the Green Deal will be elevated in importance. In the short-term, protecting incomes should be prioritised. In the recovery phase, member states should consider what jobs in carbon-intensive economic activities are precarious and whether the focus should be on jobs as such or on the sectors in which they are located. The industrial strategy of the EU, released while the virus outbreak accelerated, would have to remain coherent with the Green Deal. This will be even more true post-crisis due to the large-scale fiscal policy interventions foreseen." According to the article "The European Green Deal must be at the hearth of the COVID-19 recovery" [19], as the title highlighted, the coronavirus crisis recovery is a chance to redesign a sustainable, inclusive economy, revitalizing industry, preserving vital biodiversity systems and tackling climate change. Secondly, the European stimulus packages will shape Europe's economies and societies for decades to come and we should make sure these lead to a greener, more resilient and inclusive future.

Going back specifically on the building sector, the "Renovation wave" initiative – introduced in the 2020 European Green Deal timeline in fig.7 – is a priority of the Green Deal and the recovery plan for the EU, aiming at increasing the rate and quality of renovation of existing buildings and thereby helping decarbonise the building stock. Given the relatively labourintensive nature of the renovation work and the way in which this matches the "green, digital and resilient" ambition of the Commission recovery package, the Next Generation EU Communication talks about regulatory and financial support to "at least doubling the annual renovation rate of existing building stock." So, the European Commission opened a public consultation on boosting the building renovation across Europe [20].

## *1.4 Through the digitalization process: from automated to digitalized buildings*

In order to understand the importance and the necessity of introducing the Smart Readiness Indicator and its role and value both for the occupants and the policy makers on the other hand, an overview on the digitalization and its impacts on energy and building sector is required. In a report called "Digitalisation and energy" [21], the International Environmental Agency put in evidence the real and strong meaning of the link between the world of digitalization and related new technologies and the challenges of the diverse energy demand sectors, so also the buildings' one. Over the next years, by the use of digital technologies, the energy systems around the world would be more connected, intelligent, efficient, reliable and sustainable, that in other words means creating an innovative mechanism capable to deliver energy at the right time, in the right place and at the lowest possible cost. These are the key aspects of the digitalization involving the energy sector. Moreover, the digital revolution touches safety, productivity, accessibility and sustainability of the energy systems, involving markets and business and changing them. Going deeper in the building sector, dealing with a digitalized building and/or a digitalized community of buildings means exploiting the responsiveness of devices and services, which become also capable to predict the occupants' behaviour. Another advantage is enabling the demand response, to reduce the peak loads, to shed them and to store energy, according to the real time energy prices. A third big consequence of the digitalization of the building services is connected to the improvement of the monitoring and control system, having now the instruments to predict and measure the real-time energy performance of buildings; in this way there is the possibility to act with maintenance immediately when it is needed, to improve the building operation mechanisms, to save energy where and when it is possible.


*Figure 8 - Digitalisation potential impact on transport, buildings and industry; IEA [21]*

According to the IEA analysis, as underlined by the graph above, there are different implications depending on the kind of technology and its field of applications; if on one hand these appliances reduce the energy intensity of providing goods and services, on the other hand there would be rebound effects increasing the energy use. The framework of interest is the one related to the building sectors, so the impacts of digitalisation on it are now deeper discussed.

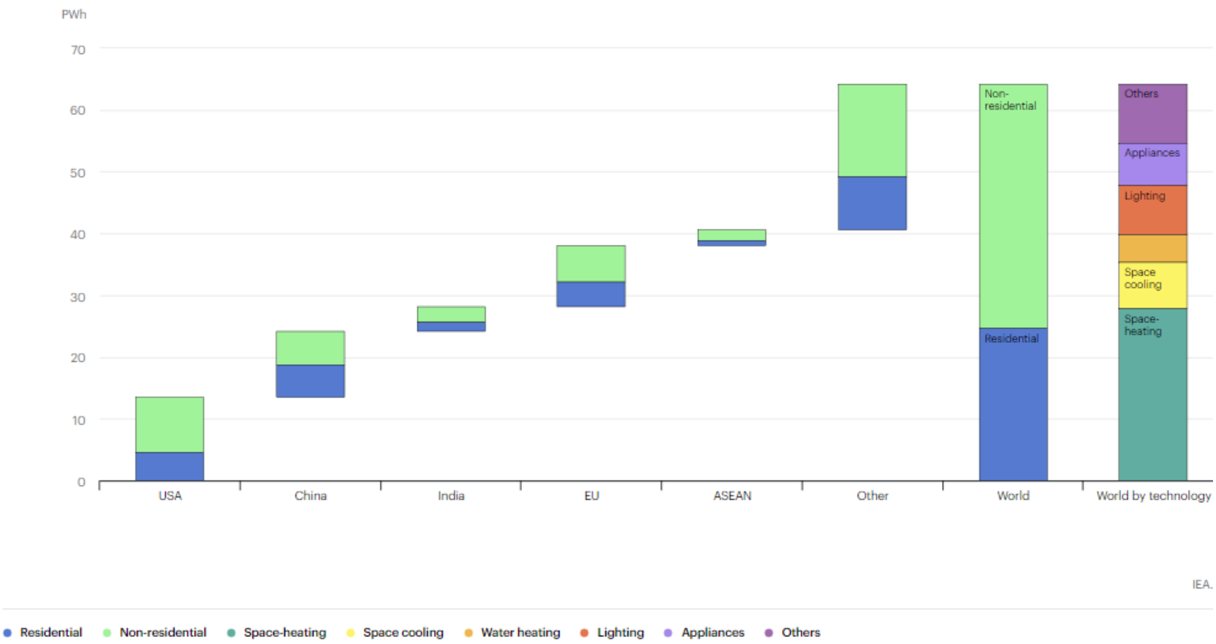


*Figure 9 - Cumulative energy savings in buildings from widespread digitalisation in selected countries, 2017-2040; IEA [21]*

In the IEA Central scenario, electricity use in buildings is set to nearly double from 2014 to 2040, so that a huge increase in power generation and network capacity would be required. Thanks to digital services and technologies like smart thermostats and lighting, the total energy use could be cut between 2017 and 2040 (the study was conducted during 2017) of as much as 10% with respect to the Central Scenario, assumed limited rebound effects. It is a big and relevant evidence about the positive impacts of digitalisation in buildings, being aware that it is only from the point of view of the building performance and consumption and that there are a lot of positive aspects also from the point of view of users, grid, environment.

To go deeper in the details of a digitalized building, a focus is needed on the building digitalisation structure, which is a milestone in the transition process from automated buildings to smart buildings. The core of an automated built environment is given by the central system, made by the central control system and sensors, networks, actuators:

- sensors are useful to measure quantities and collect data, in order to elaborate useful information for the facility manager, for the assessment of indicators or to give and receive feedback from the users. Sensors are able to measure temperature, relative humidity, air flow, gas leak etc., in relation to the building operation, presence of smoke, flammable gases for safety check, electric power/energy, voltage, thermal power/energy, to control energy use.
- actuators are the instruments through which the message of a sensor is received and carried from it in order to translate the measured quantity by changing or adjusting the settings of an appliance or the status of a certain component; the central unit or a dimmer are actuators, examples of appliances are heating, lighting, recovery ventilation.

The overall framework of sensors, smart meters, actuators represents the hardware of the built environment; these instruments automate the building. To achieve the digitalisation, the steps involving the acquisition of data, their processing and storage need to be faced, so that the artificial intelligent of building is required; the IOT, Internet of Things, represents an effective instrument to be used, in accordance to the AI, Artificial Intelligent.

## *1.5 Towards smart buildings: state-of-the-art and characteristics of a smart built environment*

In this framework, discussing about the great relevance of the digitalization revolution, the characteristics of a smart-ready built environment can be better defined and understood. In a report about the mapping of Europe around this theme, published in February 2017 [22], titled

“Is Europe ready for the smart building revolution?”, the smart built environment is defined according to five key features, so five aspects leading to the definition of what it is needed in order to deal with a smart solution; efficiency and health, dynamic operability, responsive energy system, renewable energy uptake and dynamic and self-learning control system are the key elements. In this multi-definition it is evident the link with the Long-Term Strategies, in particular the need to achieve improvements in performance – from the point of view of the building but of course in relation to the occupants too – and also the importance already underlined about responsiveness of the systems and their dynamicity concerning the self-learning capabilities. In this research carried on by the BPIE to assess the smart-ready level for the EU Member States, twelve essential characteristics are analysed, by the use of fifteen indicators regarding their possible quantification.

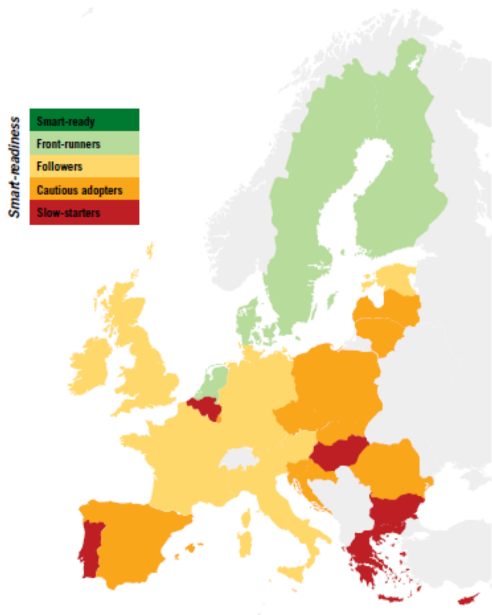


*Figure 10 - Smart readiness across Europe; BPIE [22]*

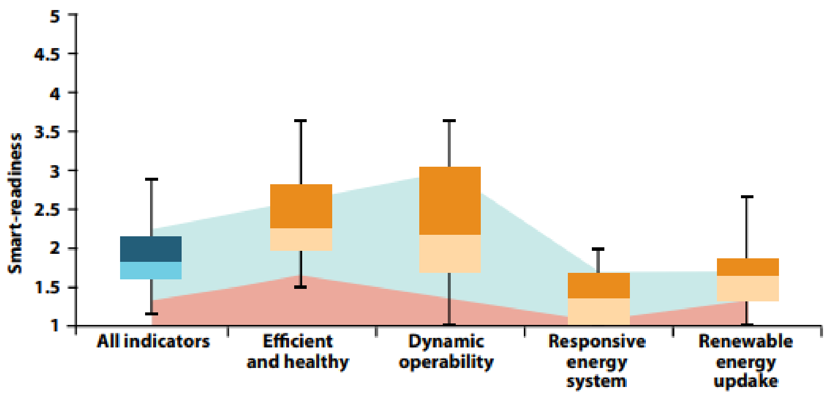


*Figure 11 - Box plot showing distribution of average score for all countries; BPIE [22]*

According to the fig. 10, it is clear that the European countries are not currently ready for the smart revolution. No country is fully ready to take advantage of the benefits linked to the interconnected smart systems. The box plot of fig.11 shows how the biggest differences among countries are in terms of efficiency, health and also about dynamic operability. A deeper focus on the Italian situation, according to the studies of BPIE, leads to the following details:

*Table 2 - Table summarizing the Italian levels of smartness; adapted from BPIE data [22]*

| | |
|---|---|
| **BUILDING PERFORMANCE** | |
| **Building envelope (U-value)** | slow starters |
| **Final energy consumption** | cautions adopters |
| **HEALTHY LIVING AND WORKING ENVIRONMENT** | cautions adopters |
| **ABILITY TO KEEP ADEQUATELY WARM/COOL** | cautions adopters |
| **SMART METER DEPLOYMENT** | smart ready |
| **DYNAMIC MARKET** | |
| **Flexibility in the market** | front runners |
| **Dynamic pricing** | cautions adopters |
| **CONNECTIVITY** | cautions adopters |
| **DEMAND RESPONSE** | slow starters |
| **BUILDING ENERGY STORAGE** | slow starters |
| **ELECTRIC VEHICLES** | slow starters |
| **EFFICIENT HEATING CAPACITY** | |
| **District Heating** | slow starters |
| **Heat Pump** | followers |
| **RENEWABLE ENERGY** | cautions adopters |
| **PHOTOVOLTAICS** | cautions adopters |

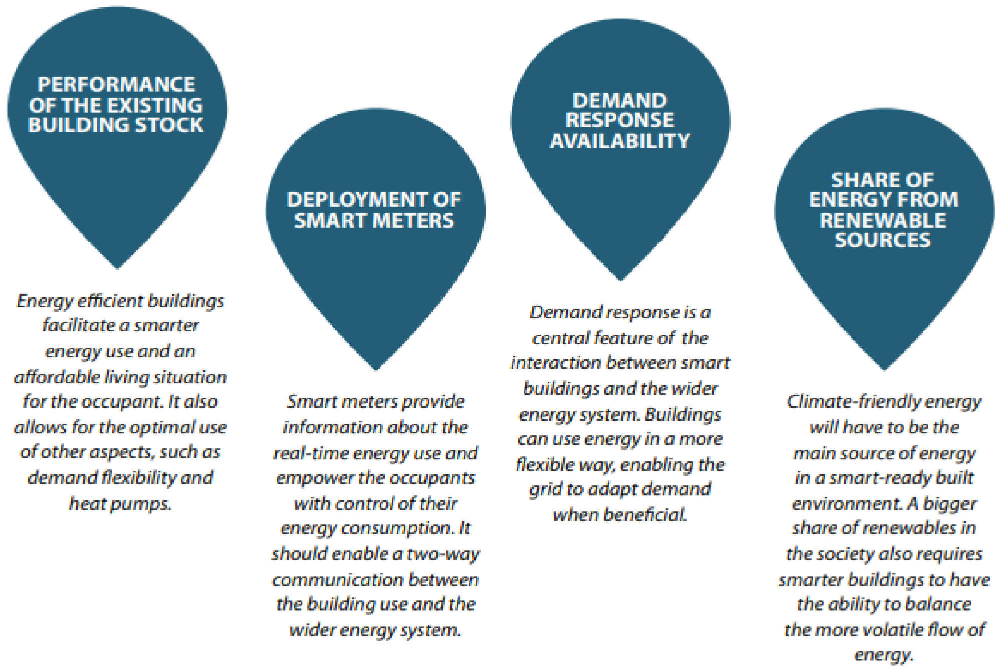


*Figure 12 - The four key indicators under the spotlight; BPIE [22]*

About the building performance, it becomes of relevance to distinguish, talking about smartness and digital renovation, the designed performance and the actual performance, as better explained in the next section. In particular, "After finalising construction or renovation, elements are adjusted to achieve the desired comfort level of buildings. […] Very often, this behaviour leads to the calculated final energy demand and the real-measured final energy demand being very different. Monitoring systems and dynamic, or even self-learning, control systems could help mitigate this mismatch and ensure a high actual energy performance of the building." [22]

At this point, considering that the thesis focuses on the effectiveness of the Smart Readiness Indicator, a comment is needed about the importance of the quantitative analysis in this field and the use of indicators as essential instruments to better face problems and to better achieve effective solutions, also in terms of performance gap – often linked to high differences between the project and a building with occupants interacting with it and its systems. Moreover, before quantifying, it is necessary to understand that the quantification is not only for energy data and measures, but also health, comfort, environmental impacts are involved in a complete analysis of the built environment and its performance; "co-benefits of energy efficiency like the reduction of emissions, health and economic benefits can be significantly higher than the cost of energy measures" [23].

Another point is the one related to the smart meters, another key factor towards the smart building revolution; "the EU aims to replace at least 80% of electricity meters by 2020, wherever it is cost-effective to do so" [24]. According to the Joint Research Centre, "by 2020, it is expected that almost 72% of European consumers will have a smart meter for electricity, while 40% will have one for gas" [25]. Italy in this field is a step forward; like Sweden and Finland, over 95% of homes are equipped with smart meters, [26] and [27]. Another important feature is the Demand Response – as enabler of security of supply –, RES integration, increased market competition and end-user empowerment, involving different possible actions like shifting, on-site generation etc. Most of the countries are closed or have very little participation of Demand Response, Italy is among them. Finally, a faster and more efficient integration of renewables in the conventional energy supply systems is of course an essential feature of the smart buildings renovation, even if the share of RES appears to be not diffused in Europe yet, also in Italy. In this Report of BPIE, also the Smart Readiness Indicator is mentioned, underlining the importance of having a rating scheme and not only with the objective to assess the current situation, but also to lead the Europe to a smart and decarbonised building stock by 2050. "A smart building revolution is not just about upgrading our building stock, mitigating emissions or balancing energy flows, it is about delivering direct benefits for EU citizens in terms of lower energy bills and warmer homes, and wider benefits for Europe as a whole with jobs created and boosts to economic growth" [22].

According to the executive summary of the Smart Building Report 2019 [28], the main key components of a smart building can be summarised as following:

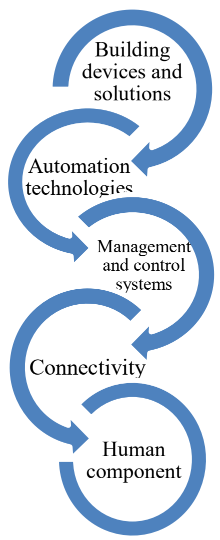


*Figure 13 - The 5 key components of a smart building; Smart Building Report 2019 [28]*

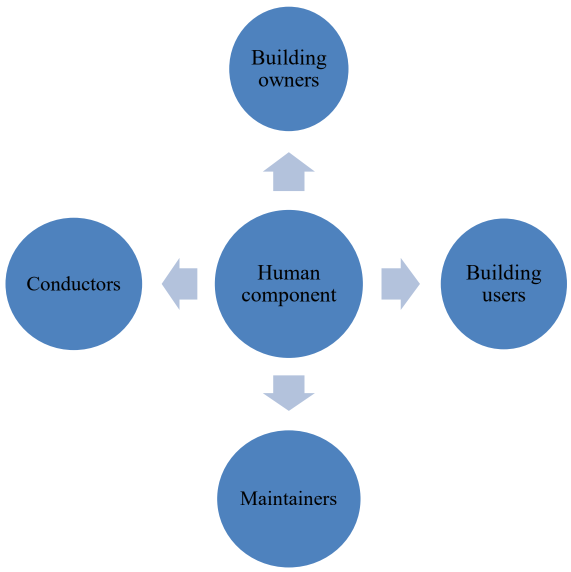


*Figure 14 - The human component of a smart built environment; adapted from Smart Building Report 2019 [28]*

The human component is the driving factor of the smart building revolution; it is made by people who manage, invest and/or directly exploit the benefits and services of the built environment. The involved benefits can be divided into:

a) Hard benefits: those benefits which can be quantified in monetary terms, as the energy savings, the optimized productivity, the predictive maintenance and the upgrade of the building value.
b) Soft benefits: those which are not directly quantified in monetary terms but connected to the improvements of the occupants' conditions, for instance in terms of sustainability, safety, comfort, tele-management, tele-control, interoperability.

As underlined by this Smart Building Report 2019, in Italy about 3.6 billion of euros were spent for smart buildings in the 2018 (the investments in connectivity are not considered in the Report):

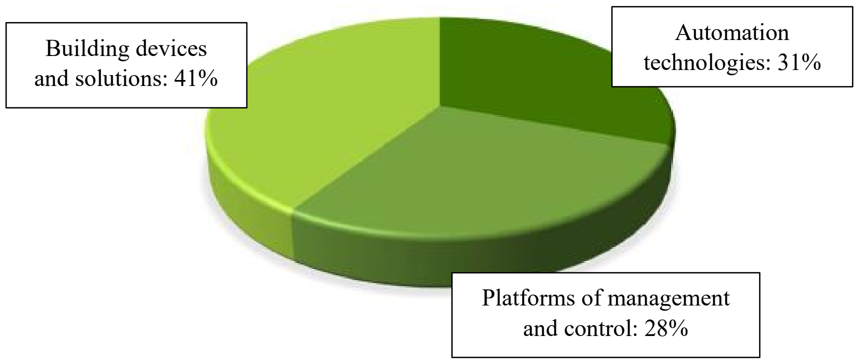


*Figure 15 - Tripartition of investments for smart features; Smart Building Report 2019 [28]*

In the following graph, there is instead a focus on the investments for the energy efficiency solutions of the year 2018 and the related percentage of the smart solutions involved in the total investments:

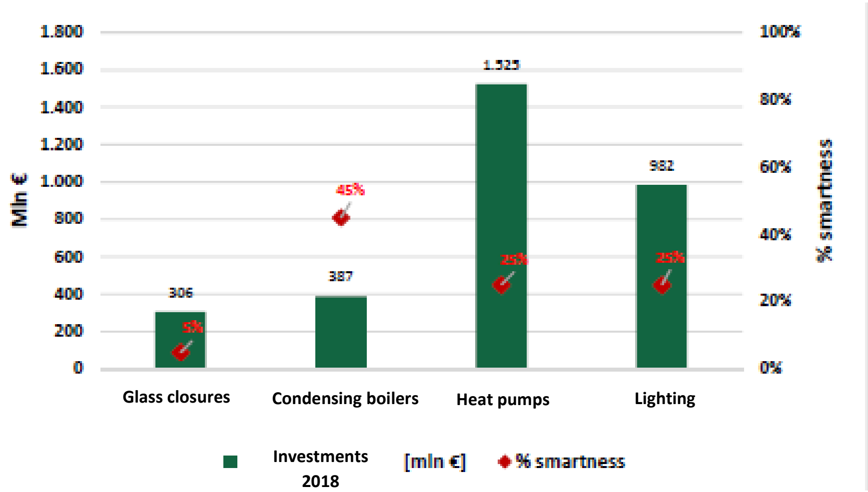


*Figure 16 - Investments 2018 in energy efficiency and % for smartness solutions; Smart Building Report 2019 [28]*

It is important to specify that the percentages of smart solutions adopted in relation to the investments do not reflect absolutely the predisposition of the involved services and technologies to the smartness, but it is referred clearly to the installed amount which can be considered smart on the total installed in 2018. Finally, a focus on the regulatory framework for the smart built environment put in evidence the efforts done at the national level and the European one, being aware of the importance of pushing towards the digital and smart revolution for the building sector.

*Table 3 - Certifications and regulation in the smart building framework; adapted from Smart Building Report 2019 [28]*

| About | Categories | Mandatory | Incentives | Certifications* |
|---|---|---|---|---|
| **Plants** | **Energy** | INECP | PREPAC | EPC |
| | | Criteri Ambientali Minimi | National fund for energy efficiency | BREEAM |
| | | RES Integration | Conto Termico 2.0 | LEED |
| | | Predisposition for the installation of infrastructures for recharge | Ecobonus | WELL |
| | | Minimum requirements | | Protocollo Itaca |
| | **Safety and security** | Criteri Ambientali Minimi | Video surveillance bonus | |
| | | Minimum requirements | Security bonus | |
| | | | Renovation bonus | |
| | | | Bonus earthquake | |
| **Digital architecture** | **Automation technologies** | Criteri Ambientali Minimi | Conto Termico 2.0 | |
| | | Minimum requirements | Ecobonus | |
| | **Platforms** | Criteri Ambientali Minimi | Conto Termico 2.0 | |
| | | | Ecobonus | |
| | | | INECP | |
| | **Connectivity** | Broadband infrastructure | | |

At this point of the Report it is mentioned the Smart Readiness Indicator, as instrument to strongly push towards the digitalization and smartness of buildings, by defining the real "level of the intelligence" of a built environment, from all the different point of view involved in the building performance – the EPC for instance is only referred to the energy performance of building.

As deeply underlined in the last part of the third chapter of the thesis, the last Interim Report released for the establishment of the SRI addresses a dedicated part to the analysis of the benefits in monetary terms, in relation to the energy savings, the increase in the investments for the relative technologies and services giving the required smartness, the requalification of the entire building sector and building energy sector.

## *1.6 The implications of smartness: the importance of post-occupancy evaluation data and the challenges for reducing the performance gap*

Moving towards a built environment as smart as possible, the "risk" is to create a big charm among the predicted energy performance and the real one; rethinking the role of the energy performance certifications in the context of an in-use building becomes a crucial step, taking care of the occupants' behaviour and the real-time answers of the building-plant systems, in order to minimize the performance gap, exploiting the monitored data.

As discussed in "Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap" [29], the sources of discrepancy between predicted and actual performance can be summarised as following:

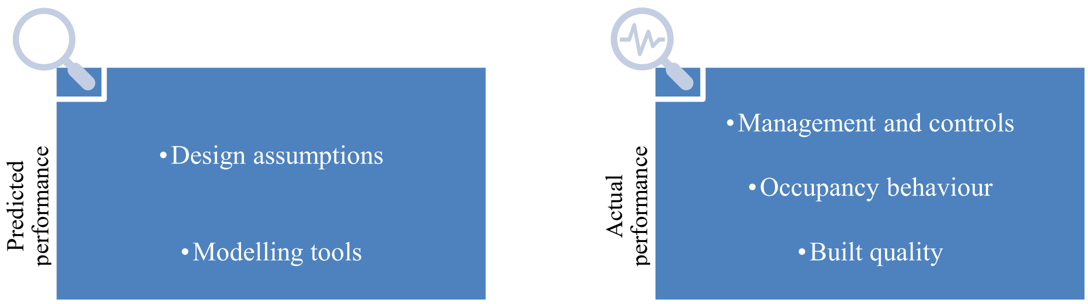


*Figure 17 - Sources of the performance gap; adapted from A.C. Menezes et al. [29]*

It is known that the input data into the energy modeling take care of several aspects involving some functions of the building which are unknown or uncertain, leading to an oversimplified model or unrealistic inputs. On the other hand, the model itself could contain errors if it is not validated and also, the chosen software must be in line with the specifications of the building to be modelled. Instead, about the actual performance, it is of course influenced by a good management and control, which can lead to a reduction in consumption with higher energy savings and a removal of unnecessary waste energy. Another point affecting the actual profile of a building is clearly the occupants' behaviour, which influences a lot the energy consumptions and it is so difficult to predict because of its irregularity. It has been demonstrated that not right assumptions about the occupants' actions are one of the main sources of uncertainties in thermal and dynamic simulation software [30]. Moreover, in a study conducted about the "Uncertainty analysis of occupant behaviour and building envelope materials in office building performance simulation", [31], the obtained results focus the attention on the importance of having a correct and better estimation of the major uncertain parameters that influence the energy consumption when designing a building. In particular, it is demonstrated how the occupants' behaviour has a significant influence in hot climates when compared to the envelope materials, which instead affect cold climates more than occupants. Finally, the third element of influence on the actual performance is referred to the quality of the construction, as gaps in insulations and thermal bridging. Moreover, in "A review of the energy performance gap and its underlying causes in non-domestic buildings" [32], the causes are listed and explained: (a) limited understanding of impact of early design decisions, (b) complexity of design, (c) uncertainty in building energy modeling (specification uncertainty, modeling uncertainty, numerical uncertainty, scenario uncertainty heuristic uncertainty), (d) inter-model variability, (e) on-site workmanship, (f) changes after design, (g) poor commissioning, (h) poor practice and malfunctioning equipment, (i) occupant behaviour, (j) measurement system limitations, (k) longitudinal variability in operation; the most impacting factors are the one related to points (c), (g), (h). It is also pointed out the segmentation of disciplines involved in the building life cycle stages, affecting the performance gap; designers, engineers and contractors usually stop to be involved in the building status once it is completed, so that the end-users have to deal with a built environment not fully understandable for them. The problem of generally assuming that the building performances are strictly in line with the design perspective create a wrong vision around what works and what doesn't, so that also the actions for improvements and savings are not simple to be conducted [33].

Having in mind this general overview on "predicted vs actual", it is of course of interest to develop a right pathway for the evolution of the energy modeling and at the same time of the energy performance certificates of the in-use building, in order to move as fast as the digitalization process and the smart building revolution do; in other words, there is the strong need to improve the interactions between grids and plants, plants and building, building and occupants but without leaving behind the simulation tools and all the instruments certifying the building operation status.

To still discuss around this big theme, a mention about a proposal among the Horizon 2020 projects is of course of interest; "Self-assessment and self-optimisation of buildings and appliances for a better energy performance" is the title of the related proposal for research, opened in July 2019 and with the deadline fixed for January 2020 [34]. In particular, the required solutions as objectives of the research would rely on collection of real-time data from the products installed and used in the building (within a system or stand-alone) and aggregation of this data at the building level, in order to follow the actual consumption and evolution of energy performance of building, individual systems and appliances; the most important focus must be on the possibility to self-assess the performance thanks to the smart appliances, systems and sensors adopted in a smart built environment, providing also information on the level of performance and related evolution. "As part of exploitation activities, proposals should also investigate how such self-assessment solutions could support a forward-looking evolution of energy performance assessment practices, both for buildings and for energy-related products. [...] At a time when the designed energy performance of buildings and appliances is improving dramatically, it would be worth gaining an accurate vision and understanding of their actual, real-life energy performance. Access to information on the actual energy performance and energy consumption is essential to help users making informed choices, both in terms of investment and in terms of usage and maintenance." [34].

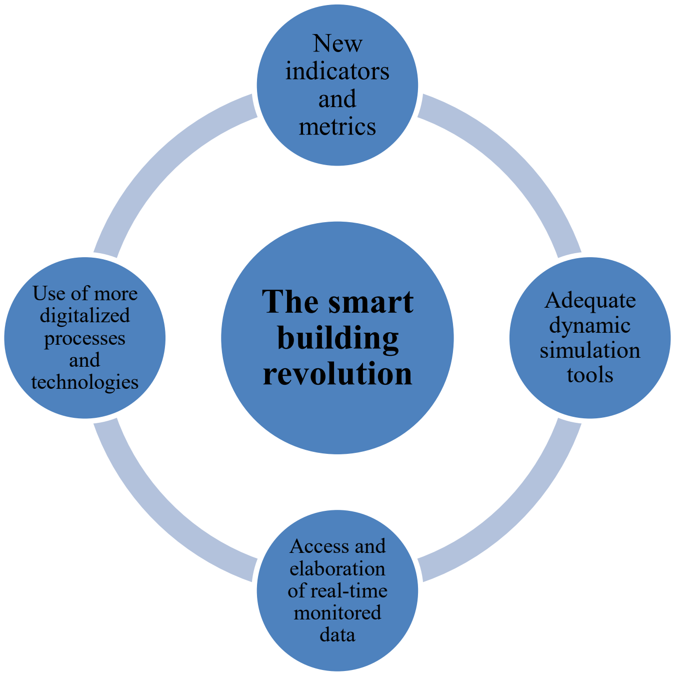


*Figure 18 - The challenges of the smart building revolution touched by this thesis*

Up to now, as expressed by the fig.18, all the aspects analysed by this work have been introduced; in the next sections, after a detailed description of the building chosen as case study (Energy Center at Politecnico di Torino) for the several purposes of the thesis, the big theme of the Smart Readiness Indicator and its test is introduced. Then, the thesis aims to explore the possible instruments to be potentially coupled to the Smart Readiness Indicator assessment to fully capture the building-plant-occupant system. Specifically, the work presents a focus on the monitoring system of the Energy Center building and on the elaboration of the collected data, and finally the modeling and simulation of the dynamic model built using EnergyPlus software, in order to compare the simulation results with the available project data, and to evaluate the potential impacts of some changes applied to the dynamic envelope on the building energy needs and on the SRI score and sub-scores, to test also in this sense the effectiveness of the Indicator to combine the topics of building energy efficiency and building readiness to smartness.

# 2. Why the Energy Center building as case study?

***The main features of this complete and complex building chosen for the analysis***

To better analyse and discuss the need of new metrics and tools in order to evaluate the performance of a building during its operation, taking care of its readiness to the needs of the grid and of the occupants too, a complex and complete building is taken as case study, the Energy Center building of Turin.

## *2.1 The main features of the Energy Center building*

*Figure 19 - The Energy Center building in Turin*

The Energy Center is a building completed in 2017. The challenge was creating a space to merge different actors and knowledge, pursuing together the innovation in energy and environmental field. It can be classified as an office building, where public and private entities can meet and work. The reason behind the conceptualization of the Energy Center was the idea to create an innovative and stimulating environment able to put in contact several actors of the energy, environmental and political fields. This combination of multi-disciplinary expertise and research areas represents the main objective of the Energy Center, idea that was exploited since its initial building design and construction phase, which represented the result of the application of innovative techniques and of multi-disciplinary researches to guarantee high levels of energy savings, smartness, comfort and innovation. The project was based on the idea to create a multi-energy environment, integrating different energy production systems and resources, among which of course renewable technologies, to be used also for further research. In addition, an advanced monitoring system and control was developed in order to achieve an efficient management of the entire building.

Built on 4 floors, its net surface is ~5441 $m^2$ and its overall volume ~30000 $m^3$.

- The basement involves: an underground parking area of about 50 parking spaces, equipped with two charging station for electric vehicles, an internal space for hosting the Energy Center Lab (feature of the building not included in the SRI assessment because out of the ordinary functionalities of an office building), an office area for researchers, the technical rooms hosting heating and cooling plants, fluid distribution system, 2 of 5 AHUs installed, the UPS group and the emergency diesel generator.

- The ground floor hosts: an exposition hall, developing for all the other floors, with a reception station; an auditorium (~150 seats); a laboratory (which is not included in the SRI assessment, with the related activities and ongoing projects).
- At the mezzanine level: the control room, where the PC room is installed, through which it is possible to manage the Supervision system of the building.
- The first, second and third floors host the office spaces accommodating private enterprises and researchers of Politecnico.

The energy demands are satisfied through two main energy vectors: electricity, through the connection to the Medium Voltage electricity grid; heat, by the connection to the District Heating network of the city of Turin. In addition, two on-field Renewable Energy Sources are exploited, a PV system of 47 kW installed for electricity production and a solar thermal plant of 30 $m^2$ for hot water production. In the Technical Room there are the systems able to satisfy the heating, cooling, DHW demand: firstly, there is a Geothermal Polyvalent Group, exploiting the aquifer as heat source in winter and heat sink in summer. It is basically used in cooling mode and there is also the possibility of heat recovery. During winter the priority is given to the District Heating network. There are three heat exchangers for three different purposes: one is for heating, one for DHW and another to feed the absorption chiller. This indirect-fired LiBr absorption chiller is not used up to now, having the possibility to reach the target with the other installed systems. Moreover, a DHW boiler of 1500 l is installed, also two TES for Hot and Cold Water both of 4000 l and a solar thermal plant capacity of 1000 l.

For the HVAC system, the solutions adopted change according to the different spaces involved. In particular, the all-air systems serve the basement and the auditorium, with a dedicated AHU each; there are also primary air systems, installed for the hall and the offices, where the terminals are made by floor or ceiling radiant panels; also, there are direct expansion split systems for the Technical Rooms, the Control Room and the UPS Room. Fan-coils are installed for laboratory and radiators for sanitary facilities. The Supervision system control all the equipment related to the HVAC system following a timer mode of a single clock. There are room control units, communication and occupancy sensors for the heat/cooling emission control and for the fluid temperature control there are control units and flow sensors. About the ventilation system, there are presence detection for supply air flow control at the room level, also control equipment for a multi-step control of the fans, temperature sensors for supply air to prevent the overheating and room/zone temperature sensors for supply air temperature control. Beside it, the system is even designed to regulate itself depending on the load: each room has its own valve, so that following the set-point of the room and being aware of the actual temperature, the ambient control can regulate the opening of the valve according to a proportional logic. In addition, focusing on the radiant floors – for the hall – and on the radiant ceiling panels – for the offices – a two-tube system has been installed: the facility manager operates the commutation from heating to cooling mode because the supply and return conduits are univocal, in particular it is done operating on the BACS that consequently acts on the commutation valves. About the sequencing of the multiple generators, both for heating and cooling, now a fixed priority list is adopted and so the building could be improved in this sense, for instance with a dynamic priority list based on current load, efficiency and/or external signals. Moreover, about the thermal energy storage, up to now only sensible storage is available.

On the lighting system side, fluorescent and LED lamps have been installed, controlled through the DALI system, a protocol technology for lighting allowing a very high granularity of control.

About the DHW system, there are control equipment with real time clock, multi sensing buffer, communication and connection to heat generation for demand transmission and scheduling device for pump.

Some of the aspects introduced in this first description of the case study will be considered in a more detailed way in the next sections of the thesis work, according to the SRI assessment and the preliminary analysis of the monitoring system.

The framework is defined: the Energy Center is a building having some prerequisites to be defined smart, being prepared to be ready to adapt in response to the needs of the occupants and of the grid and to facilitate maintenance and efficient operations in a more automated and controlled way.

## *2.2 The building assessment through the EPC and “Protocollo Itaca” certifications*

According to its Energy Performance Certificate, the Energy Center building belongs to a high class of efficiency, the A1 class.

About the “Protocollo Itaca”, it is one of the most diffuse instruments to assess the level of energetic and environmental sustainability of buildings [35]. Its added value is related to the possibility to obtain an assessment not only limited to the energy performance and efficiency of the building, but which considers also the impact on the environment and on the human health, encouraging an increase in efficiency, innovation, comfort. The protocol is compliant with the relative technical rules and national regulations; it is based on the international assessment tool SBTool, developed in the context of the Green Building Challenge. The main principles are summarised below:

- the individuation of the criteria, so the environmental themes which can lead to the measurements of the environmental performance of the building under consideration;
- the definition of benchmark to compare the performance in order to give a score in relation to the comparison;
- the weighting of the criteria which are more important or less important than the others;
- the final score defining the improvement of the performance with respect to the standard level.

In the framework of the collaboration among ITACA and UNI, in order to move from protocols to national regulations of reference, the UNI/PdR 13:2015 was introduced, replacing the ITACA Protocol referred to the residential building. From the 9$^{th}$ of July 2019 the PdR 13/2015 and the Protocol for non-residential building were substituted by the PdR 13/2019. The Energy Center building was assessed according to the National ITACA Protocol 2011, certified by iiSBE Italia, “international initiative for a Sustainable Built Environment Italia”.

*Table 4 - ITACA evaluation for the EC building; adapted by the certification by iiSBE on July 2016*

| Evaluation field | Score |
| --- | --- |
| Site quality | 3.7 |
| Resources consumptions | 3.2 |
| Environmental loads | 2.8 |
| Environmental indoor quality | 1.2 |
| Quality of service | 4.6 |
| **Overall score** | **3.0** |
| | |
| **Quality of the building** | **2.9** |
| **Quality of the location** | **4.0** |

As expressed by the certification reported above, the Energy Center received a total score of the evaluation of the executive project of 3.

In general, by focusing on the EPC and the Protocollo Itaca certification, a lot of details emerge as features of the Energy Center as built.

From now on, having clear in mind the importance of dealing with a complex and complete case study like the Energy Center building, the attention has to move from other features, by focusing on the characteristics of a smart building environment in the vision of having an indicator able to give information about the smart technologies and control strategies adopted to increase the dynamicity in operation and the readiness to adapt to the needs of the occupants and the energy grid.

# 3. Which is the state-of-the-art of the Smart Readiness Indicator assessment?

***The main steps of the proposed methodology, from the Beta Testing to the possible evolutions of the Indicator***

The Smart Readiness Indicator was introduced by the EPBD revision of the 2018. Having clear in mind that it has to be a tool helping to increase the awareness on smart technologies in buildings, both residential and commercial, this indicator requires an adequate rating scheme and needs to be easily understandable and accessible also for non-expert building users. After an introduction on the scope and assessment method of the indicator, the chapter presents the application of the methodology to the Energy Center building and the obtained score, highlighting the main strengths and weaknesses of the indicator itself.

## *3.1 Steps towards the establishment of the indicator*

At each level there is someone involving in the establishment of this indicator and/or its diffusion:

- The role of the Commission is firstly to clarify the purpose and the functionalities of the SRI. In particular, it has to promote the uptake of the optional scheme by focusing on the multiple benefits, for instance comfort that smart instruments and technologies can help deliver.
- From their side, the Member States should promote and support the use of the Indicator, once the common EU optional scheme is adopted, since this will also have a certain impact in encouraging investment on smart technologies in building sector. At national level, it would be also of interest keep doing test on public buildings.
- The local authorities have the same strategic and important rule of the Member States, since they have to directly promote and support the use of the SRI to raise awareness among citizens once the scheme for rating is adopted.

It is clear that the starting point is a proper definition of the Indicator together with the establishment of the optional rating scheme by the European Commission. The process involving the studies towards the development of the Smart Readiness Indicator has its basis as a policy initiative by the European Commission submitted as part of the proposal to amend the EPBD discussed by the European Parliament and the Council. The timeline involving the SRI is shown in the next figure, having basically to distinguish two different periods of the study, the 1$^{st}$ Technical Study is before the publication of the EPBD revision, the 2$^{nd}$ one instead follows the purposes of the Directive by focusing on the consolidation of the methodology and the features of the Indicator, including also a Public Beta Testing in which I had the possibility to take part, under the supervision of the IEEM-TEBE research group, with the Energy Center building as case study for the assessment.

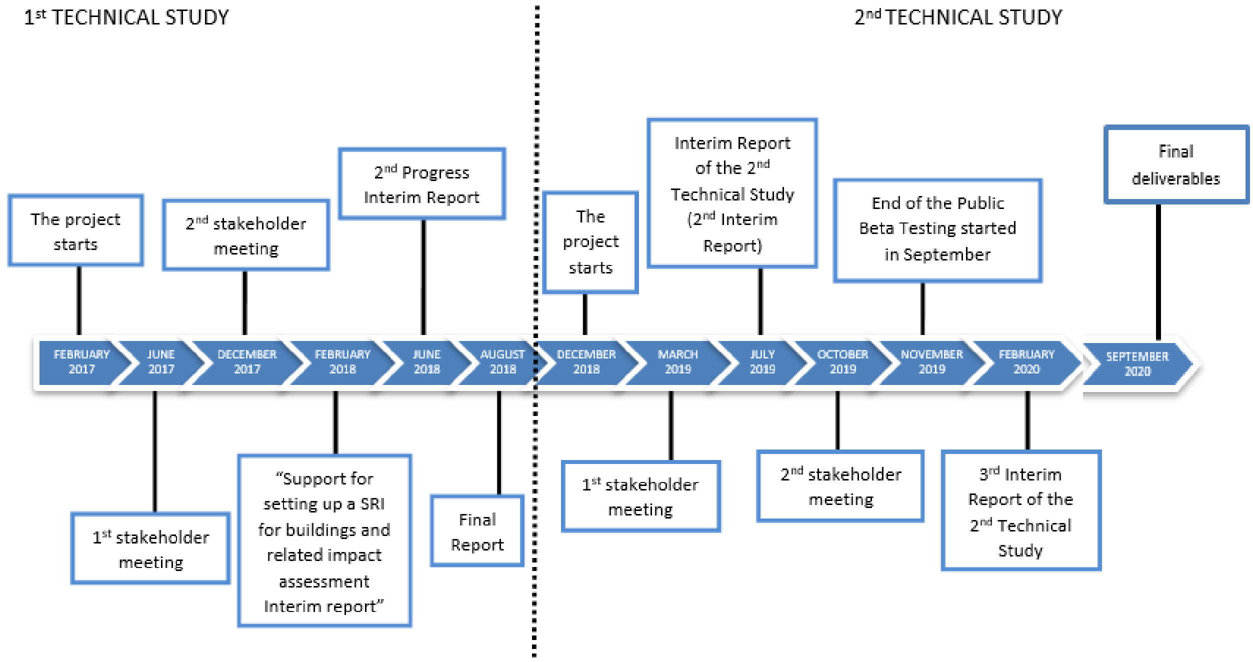


*Figure 20 - The timeline for the SRI establishment*

The 1st Technical Study was carried out by "VITO vision on technology", with "Waide Strategic Efficiency Europe", "ECOFYS Sustainable Energy for Everyone", "OFFIS Institut Fur Informatik". The 2nd Technical Study involves a consortium that spans a broad spectrum of expertise including Information and Communications Technologies, building physics, economic and environmental assessment, market and consumer analysis, and worldwide contacts, thus guaranteeing a proper scientific performance of the foreseen tasks. It is carried out by VITO and Waide, with VITO acting as the coordinator of this study. Everything concerning these studies is under the authority of the European Commission DG Energy.

As underlined by the timeline, the basis of what today is called "Smart Readiness Indicator" with a defined structure and methodology which can be tested, are in the project started in February 2017. Since in the first steps, the main goals attributable to the SRI were the same that today are available in the last documents – the final deliverables have been published on the 22nd September 2020:


*Figure 21 - SRI presentation; from 1st Technical Study, 2nd Technical Study*

This figure gives directly a first idea of the nature of the SRI. In fact, in the framework of the SRI study, in each document smartness is clearly defined as "the capability of a building and its systems to sense, interpret, communicate and actively respond in an efficient manner to the changing conditions, which are introduced by demands of the building occupants, the operation of the technical building systems or the external environment, including the energy grids" [36]. On top of this definition, it is useful to refer to the three key 'smartness' functionalities given in the Annex 1a of the revised EPBD: "The methodology shall rely on three key functionalities relating to the building and its technical building systems:

- the ability to maintain energy performance and operation of the building through the adaptation of energy consumption for example through use of energy from renewable sources;
- the ability to adapt its operation mode in response to the needs of the occupant while paying attention to the availability of user-friendliness, maintaining healthy indoor climate conditions and the ability to report on energy use;
- the flexibility of a building's overall electricity demand, including its ability to enable participation in active and passive as well as implicit and explicit demand response, in relation to the grid, for example through flexibility and load shifting capacities." [5].

The smart readiness for a building is a very powerful instrument in order to live in a more efficient, more comfortable and more connected and flexible buildings. In other words, the expected advantages of the use of smart technologies in buildings involve several aspects and actors, having in common the built environment, as introduced by the fig.22.

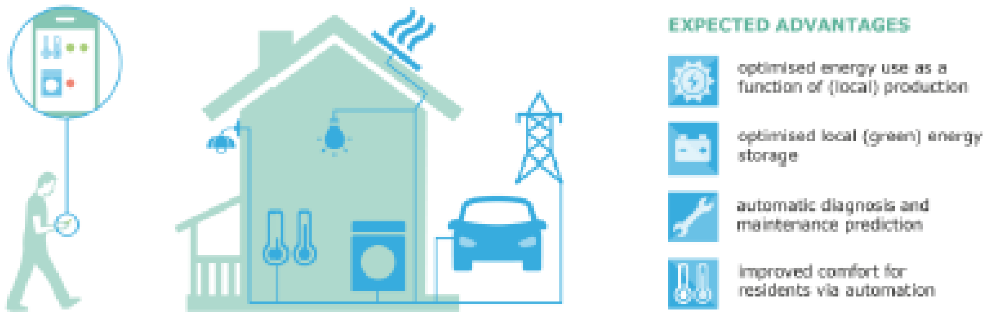


*Figure 22 - Expected advantages of smart technologies in buildings; 1st Technical Study, 2nd Technical Study documents*

To summarise the wide audience and the multi-disciplinary objectives of the Indicator, the following figure is proposed, adapted by the final deliverables, remarking the same information still present in the Interim Report of February 2020 and the one of July 2019.

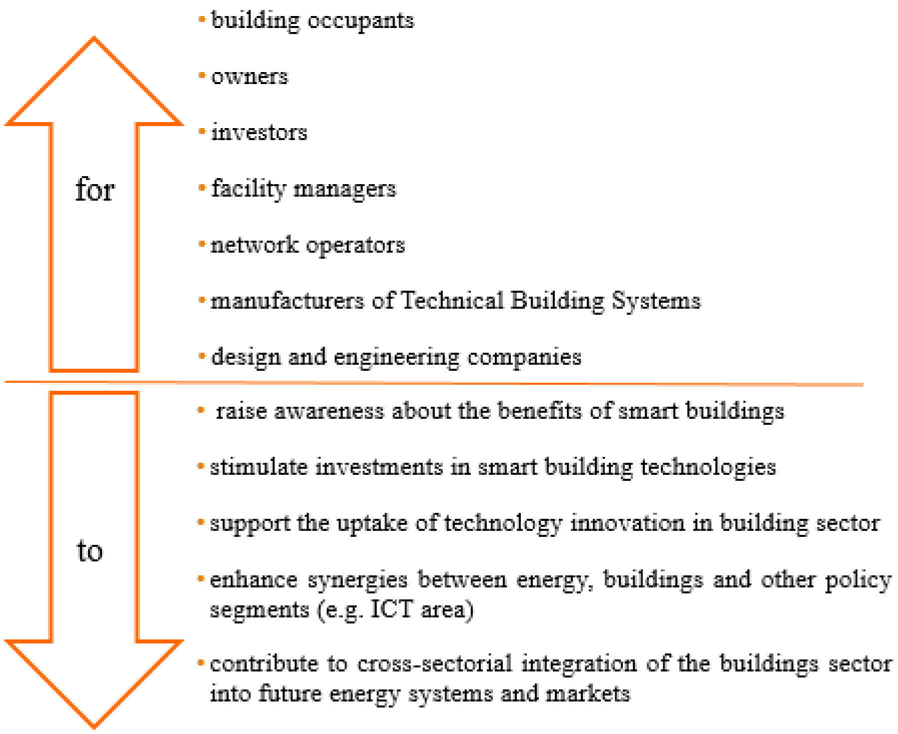


*Figure 23 - "SRI for, SRI to"*

## 3.2 The choice of the multi-criteria assessment method for the SRI

Among the possible criteria for the establishment of the Smart Readiness Indicator, a Multi-Criteria Analysis seems to have all the features needed to perform the right assessment; it is defined as an analysis of the full range of aspects related to a project, where the inputs can be the positive and negative impacts, the weights, the utility functions and among the possible outputs there are ranking and comparability assessments. The MCA appeared in the 1960s as a decision-making tool; today it is of course much more effective, considering the challenge of our world which is much more interconnected in all its several contexts and goals, for instance thinking about the projects of smart cities, as reported in the following figure:

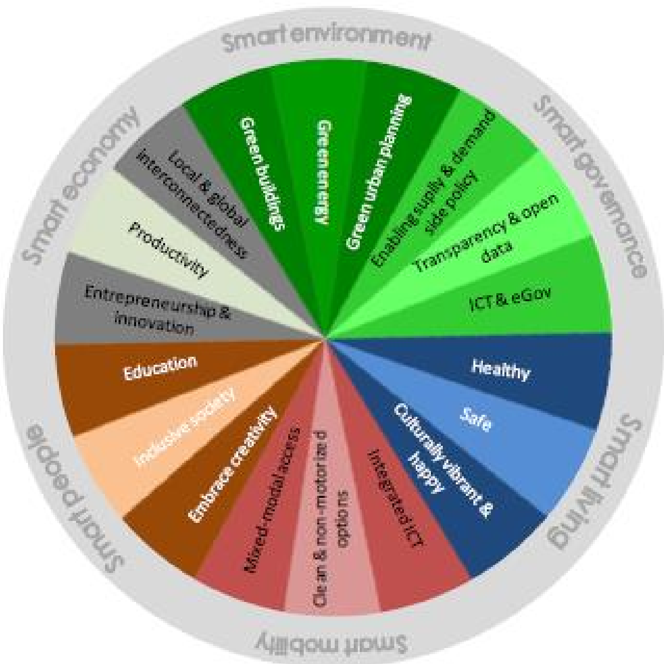


*Figure 24 - Smartness in a city; Cohen, 2013*

Its point of strength as methodology is clearly given by the possibility to take into account in the evaluation the complexity of the decision-making process. But from the other hand, its weakness can be found in the absence of a conventional procedure; there is not a unique formula or series of steps to be applied, this is why the process can become very difficult to be conducted and implemented. In the literature, talking about how the MCA works, it is underlined that it establishes preferences between options by reference to a set of objectives that the decision making body has identified, and for which it has established measurable criteria to assess the extent to which the objective have been achieved. In simpler frameworks, the process of identifying goals and criteria could be useful alone to provide the required information for the decision-makers. However, if a much higher level of detail is required, the MCA offers several ways to aggregate the data on individual criteria in order to obtain indicators of the overall performance of options. One of the classifications of this kind of method concerns the nature of the information; there are quantitative methods, qualitative methods or mixed options. In order to develop a correct assessment procedure, key questions for choosing the MCA method need to be considered, involving the kind of results needed, the stakeholders of reference, the way of sharing the outputs [37]. Having clear in mind the complexity of a multi-criteria analysis, which reflects the complexity of the several aspects of the reality it wants to take into account, the steps for conducting an MCA assessment can be synthetized in the following rules:

1. Establish the decision context, defining also the aims of the analysis and the key players to be involved;
2. Identify the options;
3. Identify the objectives and the criteria that reflect the value associated with the consequences of each option;
4. Describe the expected performance of each option against the criteria;
5. "Weighting": assign weights for each of the criteria to reflect their relative importance to the decision;
6. Combine the weights and score for each of the options to obtain an overall value;
7. Examine and comment the results;
8. Conduct a sensitivity analysis of the results to changes in scores or weights.

In particular, in the First Technical Study Final Report [38], there is a dedicated section for the Multi-Criteria Decision Making methods, because "the Smart Readiness Indicator involves the assessment of numerous impact criteria related to building's smart service capability, it is a manifestation of a multi-criteria decision-making process and like all multi-criteria assessment problems faces a challenge of how to determine preferred outcomes given the presence of more than one assessment criterion." The key concept at this point is that there is no unequivocally optimal solution in adopting this assessment procedure, "but if good methodological practice is used, the problem can be framed in a manner that allows to judgements and preferences to be compared and treated within an organised framework, maximising transparency, fairness of consideration and treatment and allows the designated decision makers to reach a collective position".

## *3.3 From the First Technical Study to the Public Beta Testing involving the Energy Center building*

As underlined by the timeline proposed in fig.20, the activities around the establishment of this indicator are still ongoing; the EPBD requires the Commission to establish by the end of 2019 the SRI as an optional common Union scheme, but the current schedule foresees an adoption in the second half of 2020. In fact, the last official documents released are the final deliverables, on September 22$^{nd}$ 2020, study accomplished under the authority of the European Commission DG Energy [39].

Being aware of the purposes of the SRI, which are the same already from the First Study, from now on there is a deep focus on the Technical Studies thanks to which today only a few steps are missed in order to obtain a final detailed rating scheme and definition for the SRI assessment. In the following section the reports "Support for setting up a Smart Readiness Indicator for buildings and related impact assessment final report" [38], and the "Second Interim Report of the Second Technical Study" [40], are commented and exploited to better explain the state-of-the-art of the SRI assessment and in particular, the Interim Report of July 2019 is the one of reference for the development of the Public Beta Testing.

The general methodological structure for the rating scheme, also the one used in the Beta Testing application, can be summarised in the following steps:

1. According to a check-list approach, identification of the smart-ready services, which must be assessed individually; their functionality level is determined. For each service, this means assigning an impact score for each of the seven impact criteria involved in the assessment.
2. Once the impact score for all the individual services is known, an aggregated impact score is evaluated for each of the nine smart-ready domains, as the ratio between individual scores of the domain services according to the functionality level assigned and theoretical maximum individual scores.
3. For each impact criterion, a total impact score is then calculated as a weighted sum of the domain impact scores; at this point the weight of a certain domain will depend on its relative importance for the considered impact.

4. The overall SRI score is then derived as a weighted sum of the seven impact criteria, again taking care of the relative importance, here of each impact criterion in defining the smart readiness of the building.

In these four steps, some words of relevance for the assessment – smart-ready services, domains, impact criteria – are introduced and need to be better explained.

### *3.3.1 Definition of relevance*

This section presents the main elements defined in the SRI framework: smart-ready services and smart-ready technologies, functionality levels, domains and impact criteria, providing a detailed description of each one.

- Smart-ready services and smart-ready technologies:
  The smart ready services satisfy a need from the user of a building, which can be the occupant but also the owner, or the energy grid it is connected to. "Ready" means that the possibility to take action exists, but it is not necessarily realized, because of cost constraints, legal or market restrictions, or occupant preferences, from the other hand it means that the equipment required to implement the service is available in the building. Services are enabled by (a combination of) smart ready technologies, but are defined in a technology neutral way, as it can be seen in some examples of services belonging to the list of services proposed. Many of the catalogue are based on international technical standards, for example BACS control functions (EN 15232-1:2017), lighting control systems (EN 15193-1:2017) and Smart Grid Use cases (IEC 62559-2:2015).
  So, the "smart ready technologies" are the practical way by which the smart ready service is delivered; it can be a digital ICT technology or a physical product or a combination thereof. For the purpose of the assessment of the SRI, the smart ready technologies could potentially:
  1) raise the energy efficiency and comfort by an increase in the controllability of the Technical Building Systems;
  2) improve the control and maintenance, automate the reporting of the energy performance of buildings and their TBSs;
  3) optimise building operations via data analytics, self-learning control systems and Model Predictive Control or other advanced methods;

4) enable buildings and their features to become active operators in a possible demand response setting.

The total possible services listed in the detailed annex are 112; the update of the default methodology proposes a streamlined list approach, based on 54 services, focusing on the services which can be practically assessed on site and which are expected to bring about the most important impacts.

- Functionality levels:

Each service can be implemented according to various degrees of smartness, referred to as "functionality levels". The higher the level, the smarter the service. There is also the possibility for each service to assign a share to a level, while the remaining share to another one. Each functionality level is translated in an impact score.

- Domains:

The smart-ready domains represent the category to which a certain service belongs to. They are nine:

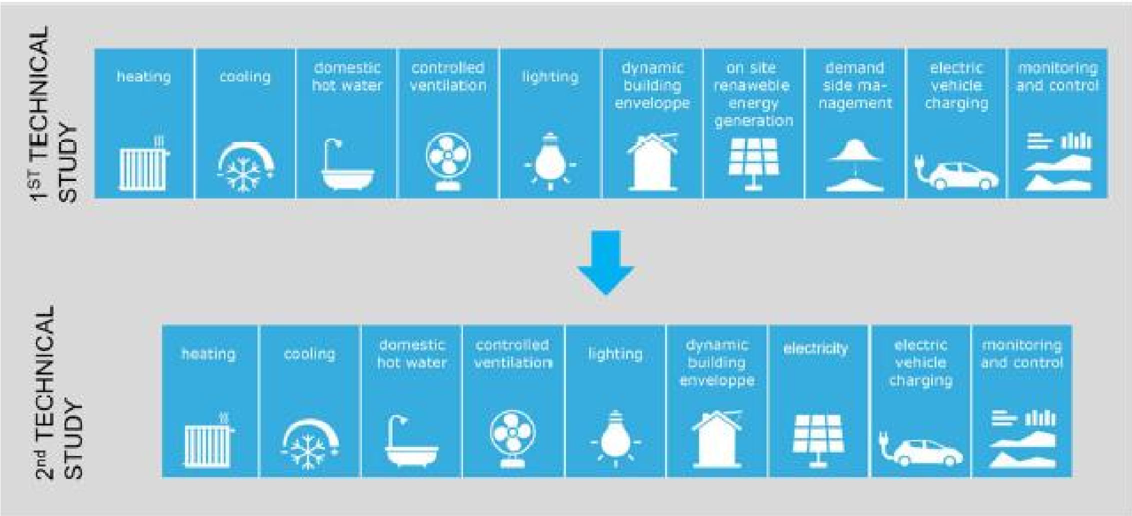


*Figure 25 - Changes to the domains; 2nd Technical Study documents*

Clearly explained by the figure above, the domains under analysis are now nine, not ten as the First Technical Study suggested. It is related to some discussions and relative decisions [40]:

a) the "on-site renewables energy generation" becomes "electricity": this decision among stakeholders has its basis in some contradictions related to the first definition and the connected services, considering firstly that some solutions may be equally beneficial towards the decarbonisation process even though not based directly on on-site generations; secondly, the presence of renewable energy sources like sun or wind does not match the definition of smartness according to the SRI, considering that the improvement of smartness can be instead associated to solutions given by storage capacity or combined heat and power; moreover, services involving storage are included in the domain, so that the name “energy generation” can seem misleading or incomplete; another point is that the “production” in terms of renewable thermal heat is already considered in the heating domain; finally, there are some services connected to electricity that are not considered in any other domains. For all of these reasons the choice to change the name of the domain to better clarify its purposes and connected services is accepted by all the member and adopted.

b) the redistribution of the services present in the “demand-side management” domain is applied: it is strictly correlated to the energy flexibility theme; since the services involved in this domain were strictly relevant for the SRI assessment, but at the same time strongly connected to certain TBSs, so often directly linked to domain like “heating”, “cooling” etc., or in other cases belonging to the “monitoring and control” features, a redistribution appears a great solution, also considering that this removal of the domain - and not of the involved services – may also ease communication, since the concept of DSM is well-known by the experts but not so clear to the wider public to which this indicator has to be as clear as possible too.

Another point related to the definition of the domains regards the feedback received on the First Technical Study concerning the possibility to involve additional domains, including transportations systems like lifts, safety and security, comfort and sustainability, noise reduction etc., so that, besides the nine principal smart-ready domains, in the last proposed assessment there is also the definition of another one called “various”, containing some services that at this point are out of scope of the assessment or not sufficiently mature to be included.

- <u>Impact criteria</u>:

  there is the need to translate the services into several impacts linked to the three EPBD pillars, so the energy performance, the building users and the energy grid.

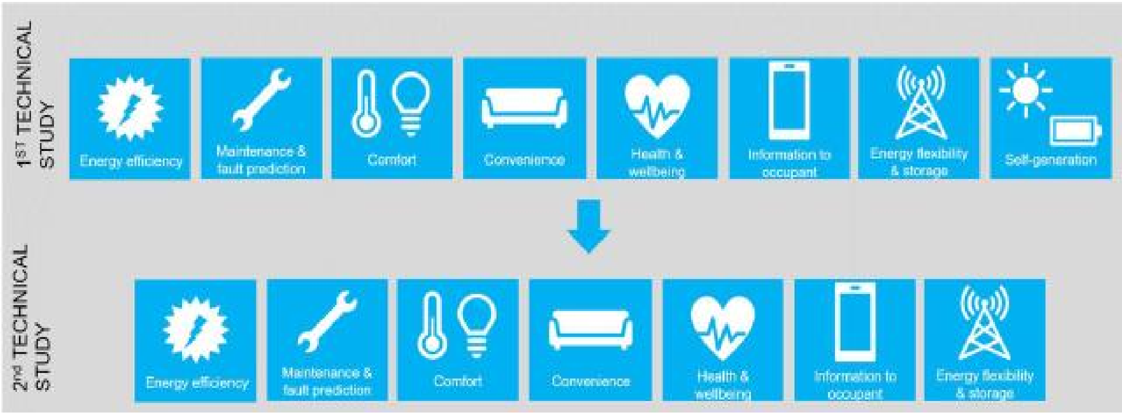


*Figure 26 - Changes to the impact criteria; 2nd Technical Study documents*

As for domains, also for the impact criteria a deeper analysis leads to a new repartition in the Second Technical Study with respect to the First one; in particular, an overlap among "energy flexibility and storage" and "self-generation" was revealed, so that the study team suggested to remove the impact criterium "self-generation" since the advantages of energy storage towards the grid are covered by the other mentioned impact, and the inclusion of benefits for autonomy included in the criterion "convenience". In the following lines the seven impact criteria considered in the assessment are better explained with a clear definition:

- "Energy efficiency" refers to the impacts of smart ready services on energy savings capabilities. It is not the whole energy performance of building that is considered but only the contribution made to this by smart ready technologies.
- "Energy flexibility and storage" refers to the impacts of services on the energy flexibility potential of a building.
- "Comfort" refers to the impacts of services on occupants' comfort, being the conscious and unconscious perception of the physical environment, including thermal comfort, acoustic comfort and visual performance.
- "Convenience" refers to the impacts of services on convenience for occupants, i.e. the extent to which services making life easier for the occupant, such as by requiring fewer manual interactions to control the TBS.
- "Health and well-being" refers to the impacts of services on the well-being and health of occupants. Not being harmful in this respect is a strict boundary condition required of all services included in the SRI assessment. On top of the strict basic requirements,

this category valorises the additional positive impact that some services could also provide.

- "Maintenance and fault prediction"; automated fault detection and diagnosis have the potential to significantly improve maintenance and operation of the TBSs. It also has potential impacts on the energy performance of TBSs by detecting and diagnosing inefficient operation.
- "Information to occupants" refers to the impacts of services on the provision of information on a building's operation to occupants.

### *3.3.2 The three potential assessment methods*

Having defined the most important features involving in the SRI calculation, services, domains and impact criteria, an overview of the three degrees of complexity of the methodology is proposed. An important point is that the complexity of the method – and in particular the level of streamlining of the service catalogue – affects the assessment time, which is an important feature in the overall pathway. During the Second Technical Study, according also to the suggestions of the stakeholders' questionnaire, the study team proposed three different methodological approach for the evaluation of the SRI, setting different working assumptions:

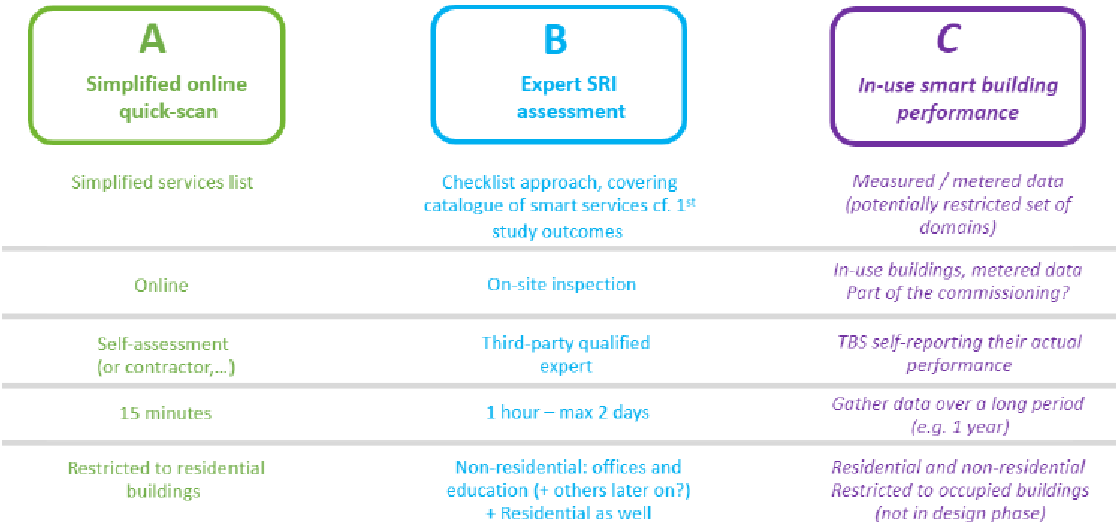


*Figure 27 - The three potential assessment methods; 2nd Technical Study documents*

Basically, two potential assessment procedures are considered: a simplified approach and a detailed one, by distinguishing between method A and method B; the light version would include a restricted number of services – 27 services – and would be addressed to simpler buildings (residential), having reduced costs and so increasing the uptake. On the other hand, the implementation of the method B would give the possibility to assess more complex buildings and more advanced services – 54 services. The third method proposed is of interest for certain stakeholders and a topical group was created to properly focus on this method C.

The methods proposed in the Beta Testing are the first two, with a priority given to the default method B:

- Method A: the simplest approach to the SRI assessment, based on a simplified quick scan through a checklist setting with a limited number of services. It could allow an online self-assessment together with a formal third-party expert assessment.
- Method B: more detailed procedure, especially involving more complex building. The approach could take more than one day, requiring also an on-site inspection by a third-party expert. It could be also performed by the facility manager of the building for instance. It remains the default method type, applicable to all kinds of buildings.

In both cases, so for method A and method B, only a third-party expert assessment would issue a formal certification.

About method C, it could be a more advanced procedure, being a metered/measured method, so it is expected to be a potential future evolution of the certification approach, considering that for instance in the long run TBS and BACS might be able to self-report functionality levels, assisting method A and B. This third method would be better developed during the next studies and future update of the SRI assessment.

### *3.3.3 The detailed method B*

Focusing on the approach of the method B, which is the one of interest for the case study but also the most complete approach at this point of the analysis, one of the first and more important step in doing the assessment is the so called “triage process”. It consists of the identification of the relevant characteristics of the building-plants systems, to find which services should be taken into account in the SRI evaluation for the building. It is essential discussed about what “relevant” stands for in the approach, also considering that doing these choices could mean increasing the maximum obtainable score so that the SRI decreases, or also, would mean getting worse or no practical comparison among different buildings. Moreover, the higher the number of services required to be assessed, the higher the assessment time required. So, the discussion involved a lot of stakeholders and members of the study team in order to find an optimum. In particular, according to the local and site-specific context, some domains and relative services are either non relevant, not applicable or not desirable. For instance, because of the location some buildings do not need cooling. Also, services like district heating and combustive heating and heat pumps are mutually exclusive. One of the point of the analysis became the difference between “smart-ready” and “smart possible”; some members wanted to follow the essence of the SRI, so by assessing the smart-ready services and not something which is not available for the building, others stressed the aim to stimulate improvements in a building by the use of SRTs. A suggestion was to consider different level of “relevance” according to the status of the building, so new construction, retrofit, existing buildings. In this discussion another point of relevance is the comparability, of course influenced by the number of services assessed. The study team concluded that if the triage process is to tailor the assessed domains to building context, transparency of the assessed domains - rather than comparability – is essential. Knowing the necessity to give guidelines in this sense, in the Interim Report of February 2020 it is clarified that:

- For some services, an evaluation is only relevant in cases where the TBSs it relates to are present. This approach is appropriate when one cannot a priori conclude that a domain should be present for that building and context.
- Some services may be mutually exclusive; if such services are not present, they do not need to be assessed during the on-site inspection.
- Some services may be absent but nonetheless desirable from a policy perspective. A suggested solution is to allow implementing bodies to define guidelines depending on contextual factors such as the relevance of specific services and domains to particular building types and climatic zones and requirements in local building codes. These services are included in the assessment [39].

### *3.3.4 The transparency of the results*

In line with these discussions about the relevance of services, strictly connected to the issue of comparability, there is the need to introduce the requirement of transparency in terms of results, which are strongly linked to the choices done during the assessment and so can better clarify also the choices adopted in the triage process. This is the discussion about the information to be communicated and so the best format of the SRI to be adopted; a first big problem is given by the contradiction between the need to communicate simply and efficiently the SRI assessment results and the complexity at the basis of the multi-criteria assessment method and so the involved aggregations, weighting factors and criteria. Of course, this point of view needs to be tailored with respect to the target audience at which the SRI has to be presented. One of the main outcomes of the study work is that the SRI must have as point of strength the possibility to be understandable and clear also to a non-expert community. So that, following these principles, in the study team about the conclusions on formatting [39] it is underlined that:

- An SRI great format could be given by the combination of a mnemonic graphic design and a matrix containing all the results of interest; this solution works well for both consumers and professional users. This configuration allows each user to see how the whole score is made of sub-scores and provides the richness of information useful for someone but giving also the possibility to appreciate only the overall score if wanted. It is suggested to use this approach for all building types and user segments.

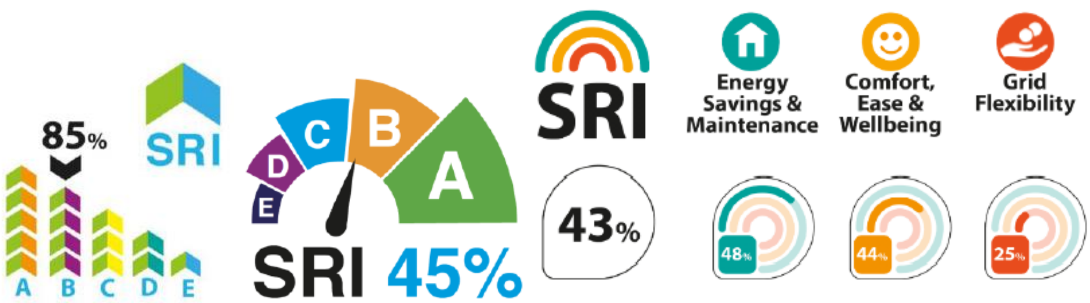


*Figure 28 - Examples of two single mnemonics and a tri-partite one to inform about results; 2nd Technical Study documents*

- About the available media, a possibility is via a certificate and/or a report with the option to see more results through an online tool. This instrument can be used not only to present the scores, but also to explain the purpose and main steps of the SRI assessment, with also the details about the highest functionality levels for services in order to underline their benefits, having also the possibility to calculate SRIs scores from raw input data in order to discover directly how the score could improve because of an increase in the functionality levels of the smart-ready services involved.

### *3.3.5 The weighting factors*

A very crucial point in the methodological framework is the definition of the weighting factors. There are different levels of detail according to which it is essential to do a comment on the possible higher/lower relevance of something in spite of something else, so on the possible weightings to be applied. As already decided in the First Technical Study, all the services have the same importance for the domain they belong; up to now there are no sufficient data to assign a higher relevance to a service with respect to another one competing for the same domain. So equal weightings are used for the aggregation of services at the domain level. A different approach in which not all the services would have the same importance could be implemented and be available at a later stage, when a metered, performance-based SRI will be developed (method C).

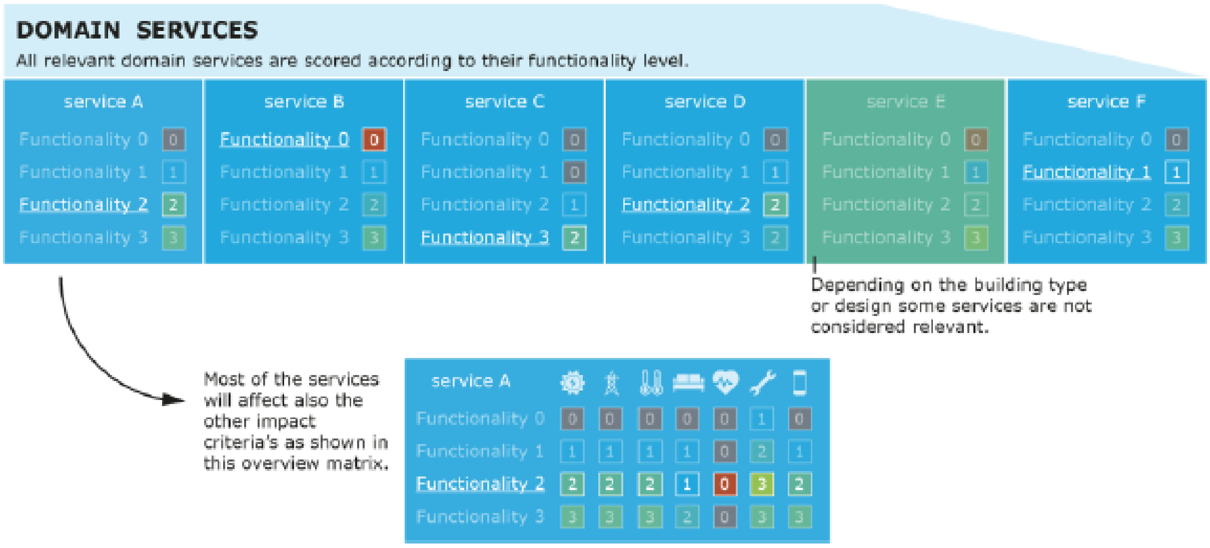


*Figure 29 - Domain services and ordinal scores for each impact; 2nd Technical Study documents*

Once the ordinal scores of the individual services for each impact criterium are aggregated to a domain score, the domain scores need to be aggregated to the single impact score. At this point it is necessary to consider the relative importance of the domain for each impact, depending on the local context and the building type. This is an important improvement with respect to the First Technical Study, where no clear roadmap through the definition of correct and possible weighting factors was already developed. Conceptually, three approaches in the definition of the weighting factors for the vertical aggregation are considered and used in a final hybrid approach: fixed weights, equal weights and energy balanced weights.

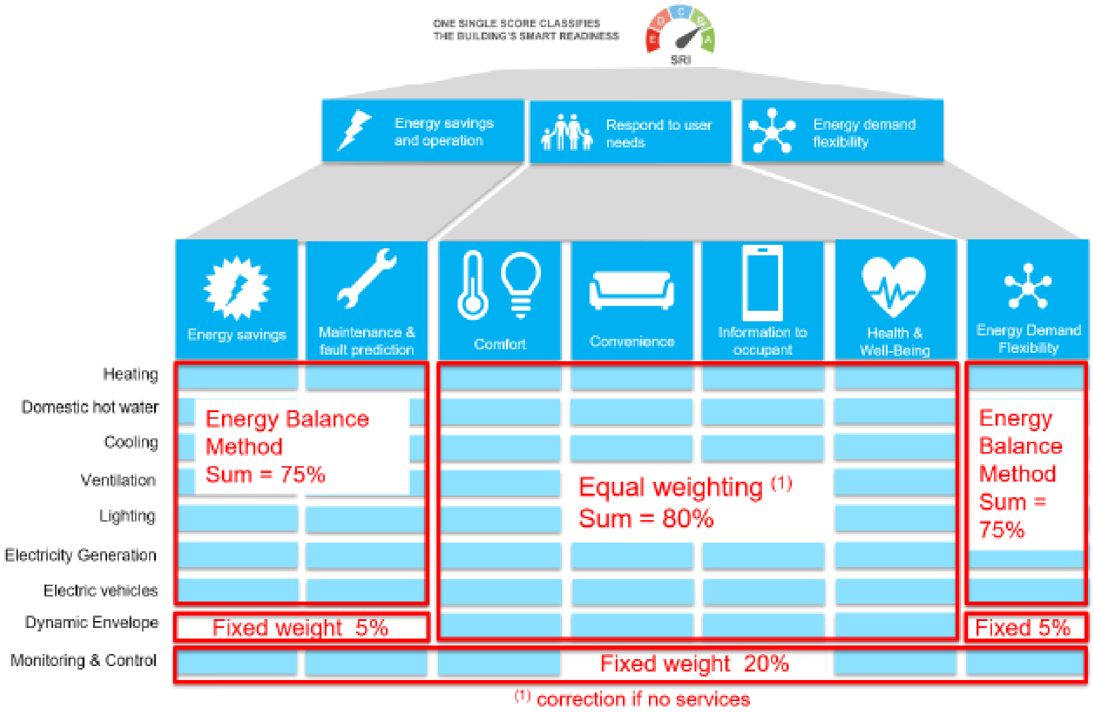


*Figure 30 - Proposed approach for domain weighting factors; 2nd Interim Report of July 2019 [40]*

In fig.30 it is summarised the approach applied also during the Beta Testing in using the weightings suggested by default. About the energy balance approach, the idea is to exploit the existing Energy Performance Certificates to derive the weighting factors for the energy-related impact criteria; in this way there is also the possibility to distinguish among different climate conditions and building types, as required. A mixed approach – by the use of statistical data taken by the national building stock but also the EPC weightings when available – is suggested. So, the derived energy balance weights are applied to "energy savings", "maintenance and fault prediction", "flexibility and storage". Not for all the domains it is possible to identify and quantify their contribution according to the energy balance approach, so that for "Monitoring and control" domain a 20% of fixed weight is proposed for each impact, while for the "Dynamic envelope" the 5% is assigned as weighting for the three impacts aforementioned; so the 75% is shared among the other domains following the energy balanced factors. About the other four impact criteria, an equal weighting sum of the 80% – having confirmed the fixed 20% of "monitoring and control" for each impact criteria – is shared among the domains considered relevant with their services during the assessment. There is the need to underline that some domains have no influence on certain impact criteria. For instance, "health and well-being" is influenced only by “Controlled ventilation”, “Lighting” and “Dynamic envelope” in the example proposed; the equal weighting sum must be shared only among these three involved domains.

The next step requires a discussion around the possible different ways to make a correct horizontal aggregation in order to weight the impact criteria for the overall SRI score. To understand the final choice towards this kind of weighting factors, it is necessary to list the three proposals for the definition of the impact criteria:

1) Proposal 1: seven impact criteria;
2) Proposal 2: three impact criteria relative to the EPBD functionality domains;
3) Proposal 3: seven impact sub-criteria that are aggregated to the three impact criteria (EPBD).

The choice among these proposals is essential in defining also the outcomes of the assessments and of course the weighting factors for the establishment of the whole score. In conclusion, the study team decides for a hybrid approach, so the Proposal 3 is chosen, considering both levels of assessment, by providing information according to the seven individual impact criteria but also by summarizing them around the three EPBD pillars. In the figure below, the relative weighting factors assigned according to this approach, which are the same applied in the Beta Testing scheme, are illustrated:

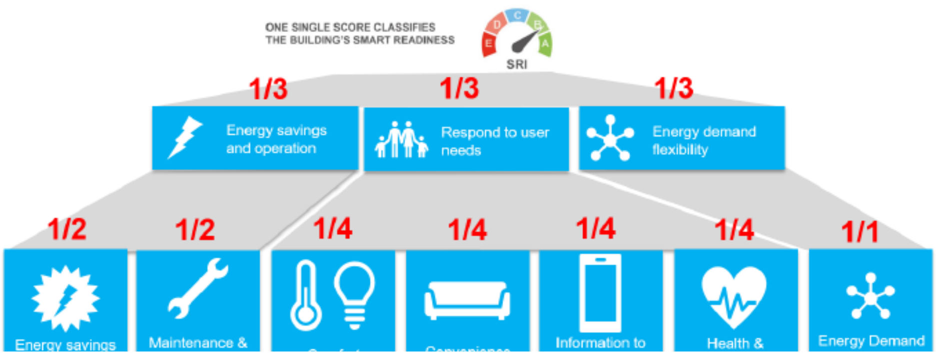


*Figure 31 – Horizontal aggregation of impact scores; 2nd Interim Report of July 2019 [40]*

## 3.4 The triage process involving the EC case study

The Public Beta Testing started in September 2019 with the idea to test the assessment procedure among the stakeholder members and anybody who wants to give feedback and suggestions based on the experience of the evaluation on their own case study. I took part to this test with the support of the TEBE-IEEM research group at DENERG of Politecnico di Torino, assessing the Energy Center building of Turin.

### 3.4.1 Input and output of the Beta Testing

For the Beta Testing participation, some excel sheets are required to be filled in, in particular a document is for the method B (the default method) and one – optional – for the method A, which during the thesis work I also considered in order to make some comments. By completing the "Building information" sheet, the triage process was made, leading to 48 services to be assessed over the total 54 listed, a high number which was not a surprise also for the other people involved in the assessment - two researchers and the facility manager of the building – considering the high level of complexity and the idea according to which the Energy Center was thought and then realized.

*Table 5 - Table to summarize the triage process done for the Energy Center building*

| DOMAIN | INPUT INFORMATION | OPTIONS |
|---|---|---|
| Heating | Emission type | TABS (Thermally Activated Building System) |
| | | **Other hydronic systems (e.g. radiators)** |
| | | Non-hydronic systems (e.g. all-air) |
| | Production type | **District Heating** |
| | | Heat pump |
| | | Central heating - combustion |
| | | Central heating - other |
| | | Decentral heating (e.g. stoves) |
| | Thermal Energy Storage | **Storage present** |
| | | Storage not present |
| | Multiple Heat Generators | **Multiple generators** |
| | | Single generators |
| Domestic Hot Water | Production type | **Non-electric** |
| | | Electric (direct or integrated heat pump) |
| | Storage present | **Present** |

| | | |
|---|---|---|
| | | Not present |
| | Solar collectors | **Solar collectors present** |
| | | No solar collectors present |
| **Cooling** | Emission type | TABS (Thermally Activated Building System) |
| | | **Other hydronic systems (e.g. radiators)** |
| | | Non-hydronic systems (e.g. all-air) |
| | Thermal Energy Storage | Storage present |
| | | Storage not present |
| | Multiple Generators | **Multiple generators** |
| | | Single generators |
| **Controlled ventilation** | System type | **Mechanical ventilation** |
| | | Controlled natural ventilation |
| | Heat recovery | **Heat recovery** |
| | | No heat recovery |
| | Space heating | **Used for space heating** |
| | | Not used for space heating |
| | System sub-type | **All-air** |
| | | Combined air-water |
| | | Other |
| **Dynamic envelope** | Movable shades, screens or blinds | **Present** |
| | | Not present |
| **Electricity: renewables and storage** | On-site renewable electricity generation | **On-site renewable electricity generation** |
| | | No on-site renewable electricity generation |
| | Storage of on-site renewable energy generation | Storage present |
| | | **No storage present** |
| | CHP (Combined Heat & Power) | CHP |
| | | **No CHP** |
| **Electric Vehicle Charging** | On-site parking spots | **On-site parking** |
| | | No on-site parking |
| | Electric vehicles charging spots | **EV charging** |
| | | No EV charging |

Done these choices, which are essential considering that some services are greyed-out because of them and it is not possible to assign in those cases a functionality level – since according to the triage process they are not relevant for the case study – the assessment process reached its main step. Thanks to the knowledge of the assessors involved – their support was essential in conducting the assessment – the functionality levels were assigned. Each functionality level corresponds to a different ordinal score depending on the impact criterion.

During this evaluation step, there is also the possibility to assign a share of the functionality levels addressed to a service; if a service works according two different levels of smartness it is possible to take care of this; the share can be assigned according to the surface area involved. This option was used for the EC case study for 3 services.

The assigned functionality levels are detailed in the following table.

*Table 6 - Table to summarize the functionality levels assigned during the assessment*

| DOMAIN | SMART READY SERVICE | ASSIGNED FUNCTIONALITY LEVEL / MAX FUNCTIONALITY LEVEL |
|---|---|---|
| **Heating** | Heat emission control | 4 / 4 |
| | Control of distribution fluid temperature (supply or return air flow or water flow) | 1 / 2 |
| | Control of distribution pumps in networks | 4 / 4 |
| | Intermittent control of emission and/or distribution - One controller can control different zones | 2 / 3 |
| | Thermal Energy Storage (TES) for building heating (excluding TABS) | 0 / 2 |
| | Building pre-heating control | 1 / 2 |
| | Heat generator control (for combustion and district heating) | 1/ 2 |
| | Heat system control according to external signal (e.g. electricity tariff, gas pricing, load shedding signal etc.) | 0 / 2 |
| | Sequencing of different heat generators | 1 / 4 |
| | Reporting info regarding heating system performance | 2 / 4 |
| **DHW** | Control of DHW storage charging (using hot water generation) | 3 / 3 |
| | Control of DHW storage charging (with solar collector and supplementary heat generation) | 1 / 3 |
| | Report information regarding domestic hot water performance | 2 / 4 |
| **Cooling** | Cooling emission control | 4 / 4 |
| | Control of distribution network chilled water temperature (supply or return) | 1 / 2 |
| | Control of distribution pumps in networks | 2 / 4 |
| | Intermittent control of emission and/or distribution | 2 / 3 |
| | Interlock between heating and cooling control of emission and/or distribution | 2 / 2 |
| | Control of Thermal Energy Storage (TES) operation | 0 / 2 |
| | Generator control for cooling | 2 / 2 |
| | Sequencing of different cooling generators | 1 / 3 |
| | Report information regarding cooling system performance | 2 / 4 |
| **Controlled ventilation** | Supply air flow control at the room level | 2 / 4 |
| | Adjust the outdoor air flow or exhaust air rate | 2 / 3 |
| | Air flow or pressure control at the air handler level | 2 / 4 |
| | Room air temp. control (all-air systems) | 1 / 2 |
| | Heat recovery control: prevention of overheating | 2 / 2 |
| | Supply air temperature control | 2 / 3 |
| | Free cooling with mechanical ventilation system | 0 / 3 |
| | Reporting information regarding IAQ | 1 / 4 |

| | | |
|---|---|---|
| **Lighting** | Occupancy control for indoor lighting | 3 / 3 |
| | Control artificial lighting power based on daylight levels | 3 / 4 |
| **Dynamic envelope** | Window solar shading control | 0 / 4 (50%)<br>1 / 4 (50%) |
| | Window open/closed control, combined with HVAC system | 0 / 3 (90%)<br>3 / 3 (10%) |
| | Reporting information regarding performance | 2 / 4 |
| **Electricity** | Reporting information regarding energy generation | 2 / 4 |
| | Storage of locally generated energy | 0 / 3 |
| | Optimizing self-consumption of locally generated energy | 0 / 2 |
| **EV** | EV Charging Capacity | 2 / 3 |
| | EV Charging Grid balancing | 1 / 2 |
| | EV charging information and connectivity | 0 / 2 |
| **Monitoring and control** | Run time management of HVAC systems | 1 / 3 |
| | Detecting faults of technical building systems and providing support to the diagnosis of these faults | 1 / 2 |
| | Occupancy detection: connected services | 1 / 2 (50%)<br>2 / 2 (50%) |
| | Central reporting of TBS performance and energy use | 1 / 3 |
| | Smart Grid Integration | 0 / 1 |
| | Reporting information regarding DSM | 0 / 2 |
| | Override of DSM control | 0 / 4 |

Each of this functionality level is then translated in the calculation sheet in a certain ordinal score depending on the impact criteria. In this way each service has an ordinal score for each impact related to the functionality level assigned, while there is a maximum ordinal score corresponding to the "translation" in ordinal score of the maximum level, always impact by impact. An example is illustrated in the following figure:

| code | service | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Heating-1a** | **Heat emission control** | Service group: | Heat control - demand side | | | | | |
| **Functionality levels** | | **IMPACTS** | | | | | | |
| | | Energy savings on site | Flexibility for the grid and storage | Comfort | Convenience | Wellbeing and health | maintenance & fault prediction | information to occupants |
| level 0 | No automatic control | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| level 1 | Central automatic control (e.g. central thermostat) | + | 0 | + | + | 0 | 0 | 0 |
| level 2 | Individual room control (e.g. thermostatic valves, or electronic controller) | ++ | 0 | ++ | ++ | 0 | 0 | 0 |
| level 3 | Individual room control with communication between controllers and to BACS (e.g. scheduler, room temperature setpoint) | ++ | 0 | ++ | +++ | 0 | + | 0 |
| level 4 | Individual room control with communication and presence control | +++ | 0 | ++ | +++ | 0 | + | 0 |
| | Information sources | | | | | | | |
| | Standard? | EN 15232 | | | | | | |

*Figure 32 - Extract from the sheet "heating" from the SRI service catalogue released with the Interim Report of July [40]*

According to this table, for the heating-1a service, a functionality level of 4 / 4 means:

- 3 assigned for “energy savings on site”,
- 2 for “comfort” impact,
- 3 for “convenience”,
- 1 for “maintenance and fault prediction”,
- 0 for the others.

The assessment required about a day and a half, including the on-site inspection and the need to overcome some issues in relation to the assessment procedure which were not simply to be solved, dealing with a complex building like the Energy Center one.

The following table is taken from the “weightings” spreadsheet available in the Technical Study documents, referred to the non-residential building type and to the South Europe climate:

*Table 7 - Default weightings for vertical aggregation, Non-residential type and South Europe; Technical Study documents*

| | Energy savings on site | Flexibility for the grid and storage | Comfort | Convenience | Wellbeing and health | maintenance & fault prediction | information to occupants |
|---|---|---|---|---|---|---|---|
| Heating system | 0.31 | 0.29 | 0.13 | 0.1 | 0 | 0.31 | 0.11 |
| DHW | 0.10 | 0.10 | 0.13 | 0.1 | 0 | 0.10 | 0.11 |
| Cooling system | 0.11 | 0.11 | 0.13 | 0.1 | 0 | 0.11 | 0.11 |
| Controlled ventilation | 0.09 | 0.08 | 0.13 | 0.1 | 0.4 | 0.09 | 0.11 |
| Lighting | 0.12 | 0.11 | 0.13 | 0.1 | 0 | 0.12 | 0.00 |
| Electricity: renewables & storage | 0.02 | 0.02 | 0.00 | 0.1 | 0 | 0.02 | 0.11 |
| Dynamic Envelope | 0.05 | 0.05 | 0.13 | 0.1 | 0.4 | 0.05 | 0.11 |
| Electric Vehicle Charging | 0 | 0.05 | 0 | 0.1 | 0 | 0 | 0.11 |
| Monitoring & Control | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| | *1.00* | *1.00* | *1.00* | *1.00* | *1.00* | *1.00* | *1.00* |

The following plots present the results obtained as outputs from the Public Beta Testing for method B, once the calculation sheet was filled:

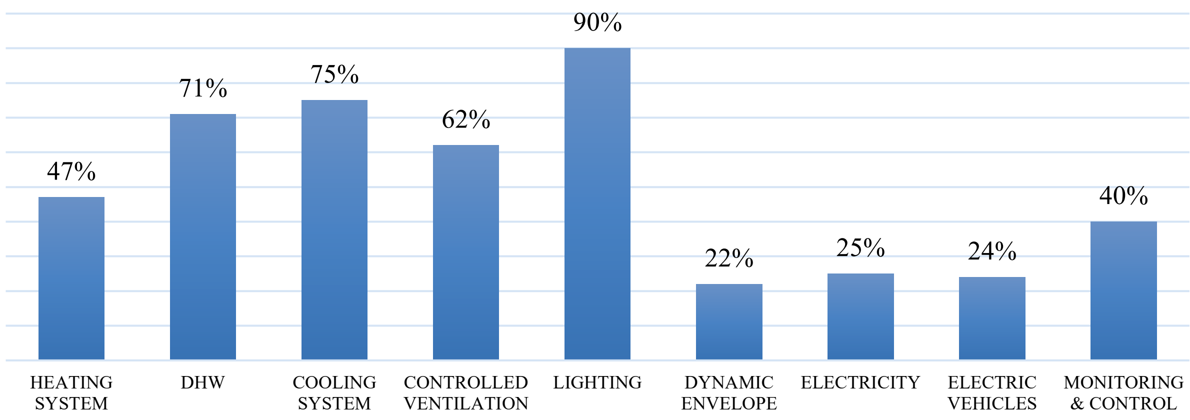


*Figure 33 - Domain sub-scores for the EC building*

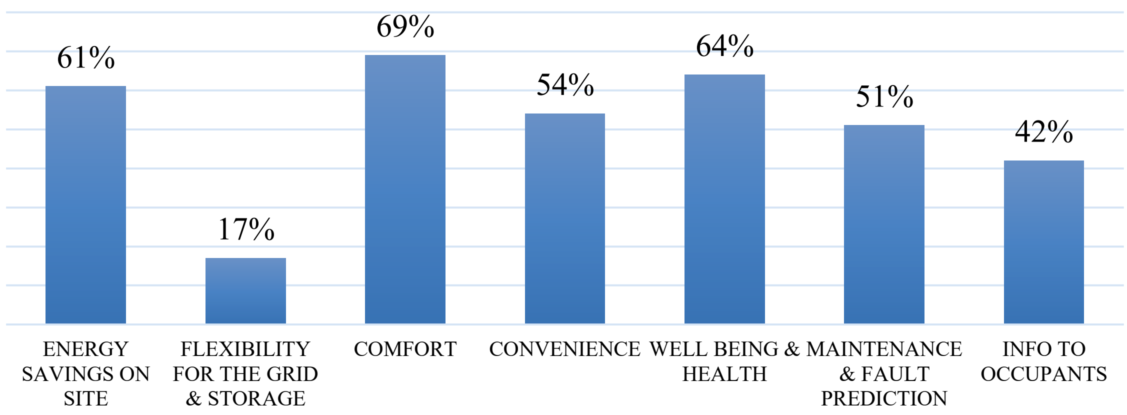


*Figure 34 - Impact sub-scores for the Energy Center building*

The overall output of the testing phase tells that the Energy Center building is smart ready for the 51%, according to the assessment of 48 smart-ready services.

### *3.4.2 Test of the quick method A*

In the Public Beta Testing there was also the possibility to try the implementation of the method A, the simplified version of the SRI assessment, in order to understand if and where there are differences among the two methods. Of course, for a complex building like the case study analysed, the method A cannot be the right instrument, dealing with a very complex building and of non-residential type. Nonetheless, a trial is made in order to test the comparability of the two assessment in terms of results, even if being aware that the method B is the most suitable;

25 services over the listed 27 services were assessed, after the triage process applied as for the method B. Of course, this assessment required less time and a lower level of detail. In the following plots there are the outputs of the methodology, compared here with the outcomes of the method B:

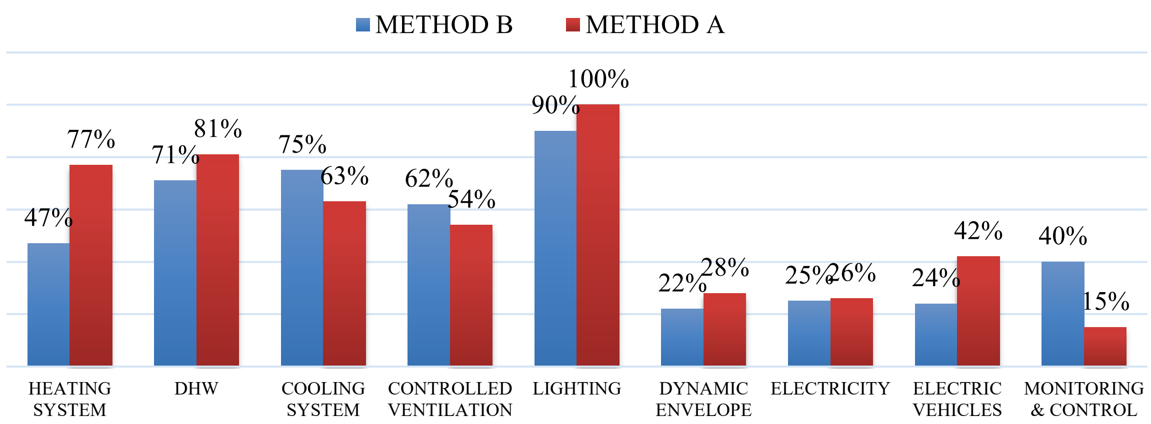


*Figure 35 - Domain scores comparison between detailed and simplified method*

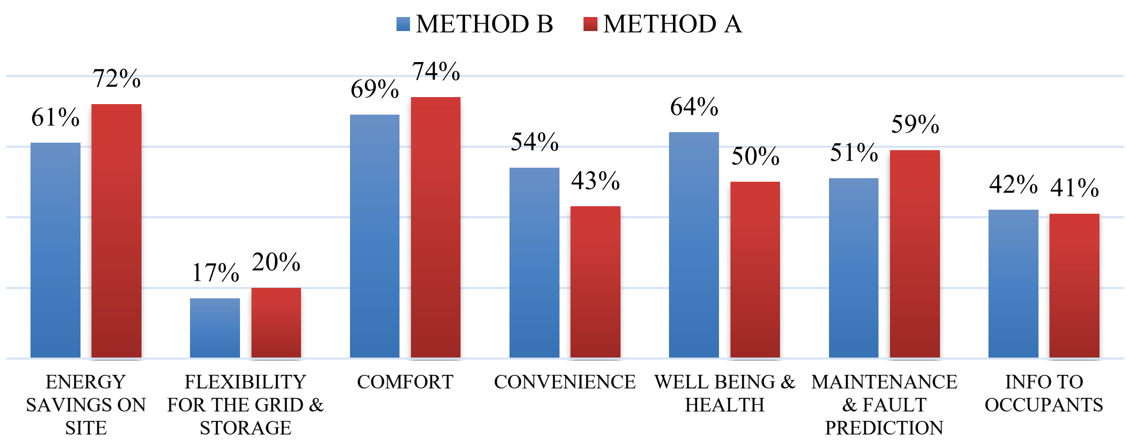


*Figure 36 - Impact scores comparison between detailed and simplified method*

The overall score which comes out by the application of the method A is 52%, having assessed 25 services over the 27 of the simplified service catalogue.

Considering that the one obtained with the detailed assessment differs only for 1% (the SRI obtained according to the method B is 51%), this suggests that the method A can be envisioned as a first basic and simple approach which can precede a more complete and complex analysis required by a more complex building. For instance, it can be a solution adopted by the user, before exploiting a third-party expert assessor, in order to face intuitively the features of the indicator and to have a first simplified overview of services. It is also evident that, surely mostly for the non-residential case, the method A cannot absolutely substitute the detailed method B; it is clear by doing an analysis of the sub-scores, considering both the domains and impact criteria results. It can be reconducted to the reduced number of services, in other word to a less detailed assessment. If seen from another point of view, it could also lead to some considerations about the choice of the services assessed because relevant for the simplified list or also to better define this simplified method in order to obtain also sub-scores in line with the method B, even if someone could use only the method A, for instance to assess a simple residential building. Once the default method is completely verified, a suggestion can be to model the simplified one in order to obtain the same results. Doing the reverse could have not the same impact, since the assessment procedure has to take care of a lot of features and different point of views and something could be missed in this sense. Another point of view can be related to the different typologies of buildings; in other word, being aware of the different possible approaches to smartness of a residential building versus an office one, a good choice can be considering the methods not comparable and useful for both, but created "ad hoc" for the type of building assessed.

### *3.4.3 Sensitivity analysis – triage process and weighting factors*

During the triage process, some discussions involved the assessors, because of different ideas around the available technical building systems present in the building and so, to be considered. In particular, at the beginning they were not sure to involve in the analysis the "Dynamic envelope" (DE) domain, knowing that the Energy Center has not movable shades, screens or blinds also according to the project documents, but on the other hand there is a smarter access to the information about windows performance and maintenance; moreover, only a reduced space located at the roof height in correspondence of the hall has the possibility to be managed in a smart way in terms of opening and closing of windows (this is the contribution for the 10% assigned to the functionality level 3 for DE-2). Also, according to the people attending the building every day, it has not the right features to allow the assessment of an envelope which is defined dynamic. In fact, this is then translated in the very low sub-score obtained for this domain at the end of the assessment, 22%. So, the idea is to analyse the influence of the inclusion of the "Dynamic envelope" domain in the procedure, knowing that its weight is not so high for the majority of the impact criteria so at the end it is expected a reduced impact on the overall result. The comparison between the outcomes of the assessment with DE and without DE are in the following plot:

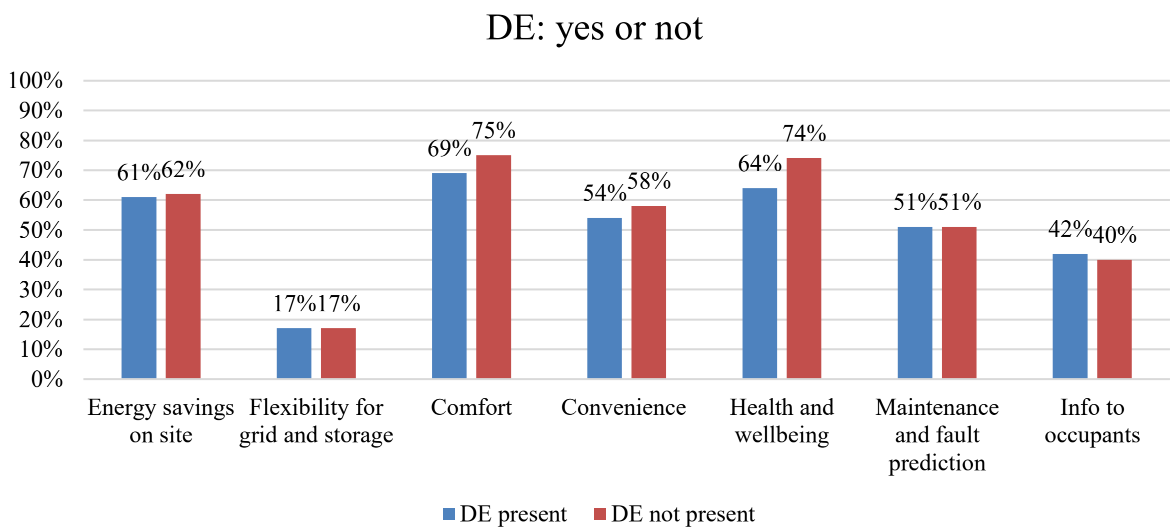


*Figure 37 - Impact scores comparison in considering or not "Dynamic envelope"*

As expected, the most affected impact by this choice is the one of "Health and well-being" for which the DE has a higher weighting factor than for the other impacts. The influence on the overall score is +2% on the final result; without considering the Dynamic Envelope domain – so being in line with the buildings as built according to the project phase – a 53% as overall SRI is assigned to the Energy Center.

This is an example to underline and discuss about the importance of the choice of the right weightings and, first of all, the necessity to conduct a triage process in line with what the building can offer in terms of its smart readiness; even if the "Dynamic envelope" domain involves a few services (three smart-ready services in total) and has a heavy influence only on some criteria, it has a certain impact in conducting the assessment in terms of result – and also in terms of assessment time – and of course choices of this type for "more impacting" domains could cause a lot of difference in the assessment, which needs to be as univocal as possible.

About this theme, there is an interesting and recent article [41] which is focused on the consequences of different assessment during the triage process, so that discrepancies and difficulties in doing the assessment are figured out. In particular, during the application of the Test to a nZEB building of Bolzano, two groups of experts are required to do firstly the assessment separately and in a second moment together; the triage processes conducted separately evidence some differences in terms of domains involved and related characteristics, and so services to be assessed. In fact, at the end the overall scores are quite different, with a delta of 13% between the two final scores, while in conducting together the testing a trade-off among the different points of view is found, discussing about the doubts and the things which should be univocal. In line with the discussion done before about the Energy Center case study, also in this study the "Dynamic envelope" domain generates confusion, in the sense that an expert group considered it as present, the second one as not present. More comments related to the outcome of this study are developed in the following section.

To discuss more about the Public Beta Testing and the work made on the Excel spreadsheets available to conduct it, some comments during the thesis work are focused on the weighting factors proposed in the table with values of default. In particular, a different procedure in defining the weighting factors – so leading to a new view on the results – is done. The first step is to analyse the accounted services and to find for which impact criteria they are considered and so, are relevant. In other words, I controlled each service, one by one, focusing on the impact scores table to find where null value was assigned even if at the highest functionality level, that in other words means no influence at all on that impact. In doing this, some differences between the default table used were found. These differences change the share of the weighting factors, for the energy balance weights and also the equal weights. I started with a focus on the energy balance procedure to assign the new shares of weight to the domains requiring the energy balance method for the impact "Flexibility for the grid and storage", since the domain "Lighting" and "Controlled ventilation" are now excluded and so there is the need to account only for "Heating system", "DHW", "Cooling system". For the impact criterium "Maintenance and fault prediction", the domain "Lighting" has to be removed from the energy balance approach.

*Table 8 – For the energy-balance approach on domains, for non-residential; on the weightings sheet of the service catalogue*

NON-RESIDENTIAL BUILDINGS

| WEIGHTINGS | North | West | South | North-East | South-East |
|---|---|---|---|---|---|
| Heating | 41.8 | 36.4 | 40.3 | 39.0 | 38.3 |
| DHW | 7.2 | 11.0 | 14.3 | 12.5 | 15.4 |
| Cooling | 12.5 | 16.9 | 15.7 | 11.2 | 9.9 |
| Ventilation | 26.2 | 19.1 | 11.7 | 24.4 | 20.1 |
| Lighting | 10.4 | 13.8 | 16.0 | 9.7 | 11.9 |
| Electricity | 2.0 | 2.8 | 2.1 | 3.1 | 4.4 |

In this table (taken from the Interim Report of February 2020 and reporting different values from the one of the Public Beta Testing Excel), the column "South" related to the building located in South Europe, contains the "alpha" value evaluated in the following way:

$\alpha_{domain} = \frac{Q_{domain}}{Q_{tot}}$, where $Q_{tot} = Q_{heating} + Q_{DHW} + Q_{cooling} + Q_{vent} + Q_{light} + Q_{elec}$

so that:

$f_{domain,imp} = \left(1 - f_{DE,imp} - f_{M\&C,imp}\right) * \alpha_{domain}$, with $f_{domain,imp}$ the weighting factor of the domain for a certain impact criterion.

These rules are applied to re-evaluate the weighting factors for “Flexibility for grid and storage” and “Maintenance and fault prediction”, considering that not all the domains from heating to electricity are involving in this ratio leading to the alpha values.

Another point is the fixed value of 5% for “Electric Vehicles” and “Dynamic Envelope”; in “Energy savings on site”, “Comfort” and “Maintenance and fault prediction” the “EV charging” domain has not impact so that its 5% is redistributed in the energy balance factors and the “Dynamic Envelope” does not affect the “Flexibility for grid and storage” impact. The final new weightings applied are reported in table 10, while the table 8 is the one used for the Beta Testing procedure.

*Table 9 - New weighting factors according to a focus on the single impact scores tables, service by service*

| southern europe - non res | Energy savings on site | Flexibility for grid and storage | Comfort | Convenience | Wellbeing and health | maintenance & fault prediction | info to occupants |
|---|---|---|---|---|---|---|---|
| Heating system | 0.31 | 0.43 | 0.16 | 0.10 | 0.00 | 0.37 | 0.11 |
| Domestic Hot Water | 0.10 | 0.14 | 0.00 | 0.10 | 0.00 | 0.12 | 0.11 |
| Cooling system | 0.11 | 0.16 | 0.16 | 0.10 | 0.00 | 0.13 | 0.11 |
| Controlled ventilation | 0.09 | 0.00 | 0.16 | 0.10 | 0.27 | 0.11 | 0.11 |
| Lighting | 0.12 | 0.00 | 0.16 | 0.10 | 0.27 | 0.00 | 0.00 |
| Electricity: renewables & storage | 0.02 | 0.02 | 0.00 | 0.10 | 0.00 | 0.02 | 0.11 |
| Dynamic Envelope | 0.05 | 0.00 | 0.16 | 0.10 | 0.27 | 0.05 | 0.11 |
| Electric Vehicle Charging | 0.00 | 0.05 | 0.00 | 0.10 | 0.00 | 0.00 | 0.11 |
| Monitoring & Control | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |
| | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

The horizontal aggregation for the impact criteria leading to the overall SRI score are still the same of the Beta Testing approach. The final results and comparisons are reported in the following plots, considering that the overall SRI score is now 50%, not 51%. In case of “Dynamic Envelope” not considered in spite of obtaining 53%, with the new weightings a score of 52% came out; so, the trend is not changed.

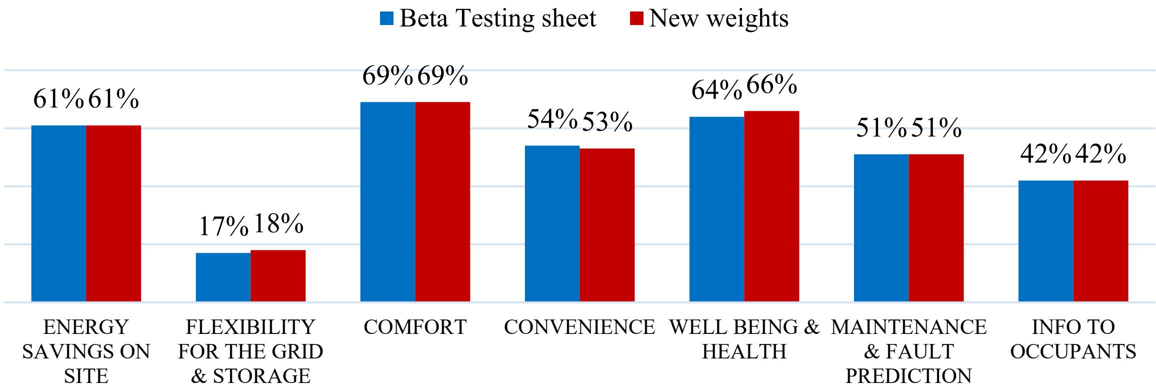


*Figure 38 - Comparison between the impact criteria sub-scores*

About the sub-scores of the domains, doing changes in the vertical aggregation leads to changes. Also, the evaluation as simple ratio among the ordinal scores domain by domain is reported:

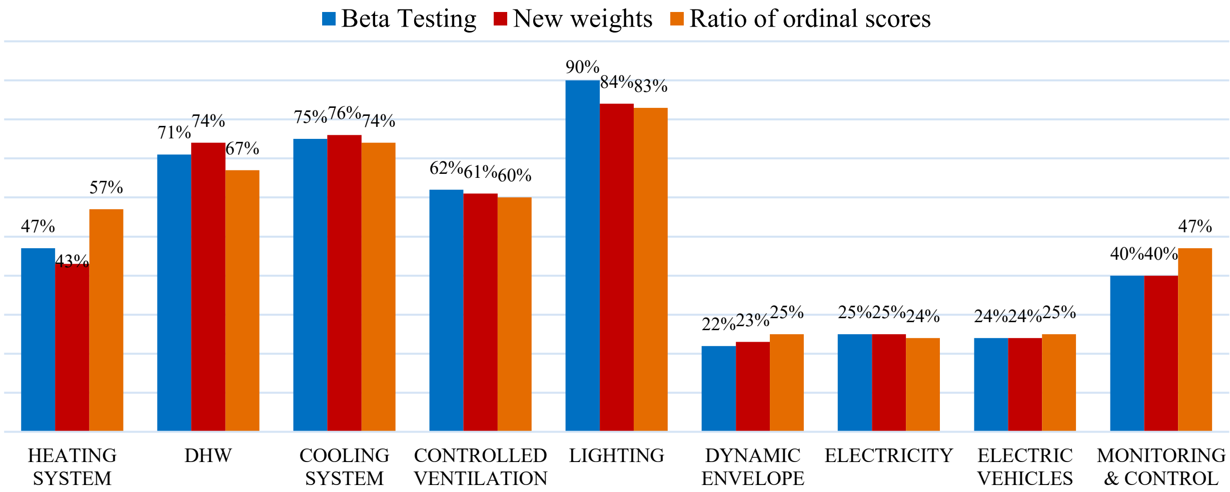


*Figure 39 - Comparison among different approaches to the evaluation of sub-scores*

As underlined by the Public Beta Testing documents, having provide the material merely for testing purposes with the main objective of exploiting the feedback received by the participants, the documents and calculation sheets are not the final and perfect solutions to be used. In particular, in the final deliverables release on 22$^{nd}$ September 2020, the weighting factors proposed are in line with my revision; a change of interest is the one regarding the ordinal scores gave to “Heating” and “Cooling” domains, for which it is recognised a certain influence also on “Health & Well-being”, so that a new redistribution of the equal weightings is needed in this new approach proposed.

To conclude this section of comments about results, I elaborated a final matrix of the overall results, under the example of the matrix proposed in the Interim reports:

*Table 10 - Matrix involving crossed domains and impacts sub-scores for the Energy Center*

| | Energy savings | Flexibility | Comfort | Convenience | Health & wellbeing | Maintenance | Info to occupants |
|---|---|---|---|---|---|---|---|
| **Heating** | 0.57 | 0.00 | 0.67 | 0.58 | 0.00 | 0.50 | 0.75 |
| **DHW** | 0.67 | 1.00 | 0.00 | 0.60 | 0.00 | 0.50 | 0.67 |
| **Cooling** | 0.75 | 1.00 | 0.75 | 0.71 | 0.00 | 0.67 | 0.67 |
| **Ventilation** | 0.50 | 0,00 | 0.75 | 0.62 | 0.70 | 0.50 | 0.33 |
| **Lighting** | 1.00 | 0.00 | 0.80 | 0.80 | 0.67 | 0.00 | 0.00 |
| **Dynamic envelope** | 0.28 | 0.00 | 0.14 | 0.12 | 0.05 | 0.50 | 0.67 |
| **Electricity** | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 0.67 |
| **EVs charging** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.67 |
| **Monitoring & Control** | 0.60 | 0.14 | 1.00 | 0.55 | 1.00 | 0.50 | 0.27 |

Here the main steps of the assessments are summarised, [39]:

1. Triage process to define relevant smart-ready services in the building or building unit;

2. Define the functionality level of each smart service;

3. Calculate the impact criterion scores for each domain, as sum of the ordinal scores of the involved services;

4. Calculate the maximum impact scores for each domain, according to the ordinal score assigned to the maximum functionality level of each service;

5. Smart-readiness score for the impact criteria as the ratio between the sum of the impact scores obtained in the step 3 and the max impact scores of step 4, but here taking care of the weighting factors of each domain for each impact criterion;

6. Smart-readiness score along the three EPBD key capabilities, taking care of the rules for the horizontal aggregation;

7. Total SRI score by weighting the calculated smart-readiness score of step 6.

In taking care of the key EPBD capabilities, the final result for the Energy Center building is the following one:

1) Energy savings and operations: 40%
2) Responds to user needs: 60%
3) Energy demand flexibility: 42%

And applying the step 7, the SRI coming out from these values is 47% in spite of 51%.

### *3.4.4 Comments and feedback through the Public Beta Testing*

One of the most interesting part both for people conducting the assessment and who received the results was the feedback part and survey to be done; in doing this, a lot of comments and suggestions come out. Here some comments of relevance are considered:

- The assessors of the Energy Center building were optimistic on the score owing to the fact the building is quite new (construction works ended in 2017). Hence, the facility manager, who assisted the whole assessment phase, considered the score of 51% as a poor result.
- About the "Building information" sheet, we propose to clarify the Heating, Cooling and Controlled ventilation sections, which seem to contain some contradictions: choosing the hydronic system as emission type for Heating, it is not possible to assess also a part of the building which could have also a non-hydronic emission type. But it is possible to do it after, in the Controlled Ventilation section, in fact after checking the use of the ventilation for space heating, there is the possibility to select an "all-air system sub-type". But here again a problem: it is not possible doing the same for the cooling system. These contradictions also affect the services which need to be assessed in the "Calculation sheet": leaving an empty space in the contradictory fields of the "Building information", some services would be greyed out, even if relevant. So, for complex

buildings, like this one, the assessor would have the possibility to choose different emission types and in the Controlled Ventilation section also the option "used for space cooling".

- Specifically on the location of the Energy Center and the assigned weighting factors, we say that it could be of relevance to distinguish between the North of Italy and the Southern part, as already suggested in the Interim Report, in the sense that probably Turin (2617 HDD) belongs less effectively to the weighting factors assigned to the “Southern Europe” countries, so a solution could be a detailed distinction according a climatic zones classification, by the Degree-Days.
- It is necessary going in the direction of a better implementation of an advanced calculation tool, as said, an available software for the 3rd party assessment and at least an online platform for the self-assessment, trying to solve problems connecting to errors in the calculation file or also limiting the possible errors from the one chosen for the evaluation.
- One of the big challenges of this kind of indicator can be found in the need of the review of the service catalogue and the methodology: the first one has surely a priority, considering also how fast the technological improvements can go. The point here is to clearer define how the assessment can practically follow the continuous technological evolution and also a critical aspect could be in the clarification of "regular" and "periodic", used to explain when the review has to be done.

This last consideration takes into account another problem related to the SRI assessment, so the necessity of the updating, considering that it is part of a context in continuous evolution and which involves a lot of changes also in a short time. According to this point, already in the Interim Report of July 2019, it is underlined the need to be in line with the technological evolution and so to address technological development and market upgrade the management of the SRI after its adoption has to follow these objectives:

- a regular, periodic review and related development work,
- a fast track option to consider the merits of promising emerging technologies and services,
- a process to agree and issue version changes and associated reporting requirements,
- an appropriate management structure [40].

## *3.5 SRI state-of-the-art: points of strength and point of weakness*

To have a clearer and detailed overview, the most important considerations coming out at this point of the thesis work are the following:

- There is the need to define a clearer roadmap for the conduction of the assessment and the implementation pathway of the SRI, being also aware of the important rule of the facility manager, mostly for more complex buildings like the non-residential, so that its support can be of relevance most of the time and also leading to a reduction of the assessment time.
- Being aware of the need to include this indicator in the definition of a building to be in line with the challenges of the present and future, the methodology has points of weakness to overcome; the optional rating scheme has to be defined in a universal way and not only for a matter of comparability but firstly to have a general and correct procedure in the assessment for a building according to which the smart readiness has to be evaluated.
- More improvements are required in terms of assignments of the ordinal score for the impacts; for some impacts like "Health and well-being" there is a lack of knowledge in terms of possible quantitative way to determine the influence of the TBSs but it is more or less the same for other services. Still concerning the relevance of the results, the criteria need to be better defined in a more accurate way; "although the SRI is based on a qualitative evaluation, each criterion should be associated with a measurable parameter that should be monitored and assessed during the building operation, enabling, as an additional effect, the comparison of the performance of smart buildings" [41].
- Of course, the study on the SRI cannot stop after the establishment of the EU optional rating scheme; an SRI which does not evolve with time and through the technological evolution lost its potential and value.

### *3.5.1 Other studies regarding the SRI*

In doing this work, it was found that in the literature there is a lack of studies about this theme, also considering it is an ongoing activity and not completely defined. In this section some comments about the SRI assessments – coming also from the First Technical Study application by other researchers – are considered. The already mentioned article about the case study of Bolzano for the Public Beta Testing [41] is one of the studies of relevance and the most recent analysed, which also allowed me to find other articles of interest.

A study in Czech Republic consists of the application of the SRI methodology to three residential buildings and an educational one, [42]; among the outcomes of the study, one is related to the weakness of the triage process, another is about the lack of information for impacts like "Health and well-being"; its score is obviously worse defined and higher than the perceived reality.

Another study [43] considers the need of doing a long manual analysis and studies to obtain a final assessment and so proposes an algorithm as a way to faster calculate the SRI in an efficient way. For the case study chosen, a sensitivity analysis concerning the number of services involved in the assessment and the weighting factors applied is conducted.

Stressing the importance of tailoring the SRI to the specific context in which the building is set, a study conducted in Helsinki [44] performed two alternative variants of the methodology, in order to discuss the problems connected to the high subjectivity of some steps, affecting the result, and the need to consider tailored approach according to a climate condition like the one of the case study, for which the advanced district heating system used must have an higher great influence.

To conclude, to be completely effective, from the point of view of the owners, of the users and of the building itself, the SRI of course needs: a) a structured and detailed implementation, with a method as univocal as possible to allow also comparability, b) an audience able to understand – even if non-expert – and becoming strongly aware of the importance of smart-ready services and technologies, c) a continuous update of the services and technologies and relative ways to assess them.

## 3.6 *“Quantitative modelling and analysis of the SRI impact at the EU level”: one of the tasks of the last Interim Report for the SRI assessment*

Among the tasks involved in the SRI definition and assessment pathway, one of interests, of course to remark how its introduction at the EU level would be crucial, it is the one modelling and analysing the impacts concerning the SRI application. The objective is to quantify, in monetary, energy and emission units first, the costs and benefits of implementing the SRI at the EU level, on a yearly and cumulative basis, then doing also a sensitivity analysis:

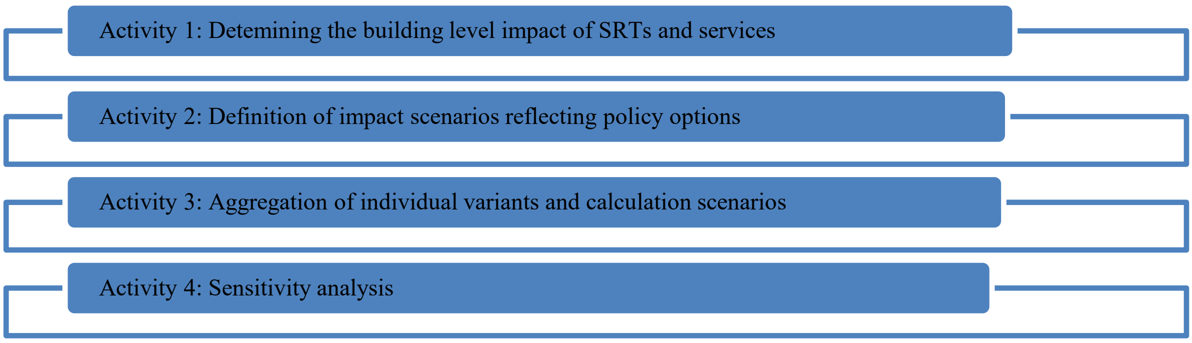


*Figure 40 - Activities of the task 4; Third Interim Report of February 2020 [39]*

In following this approach, six performance criteria have been defined:

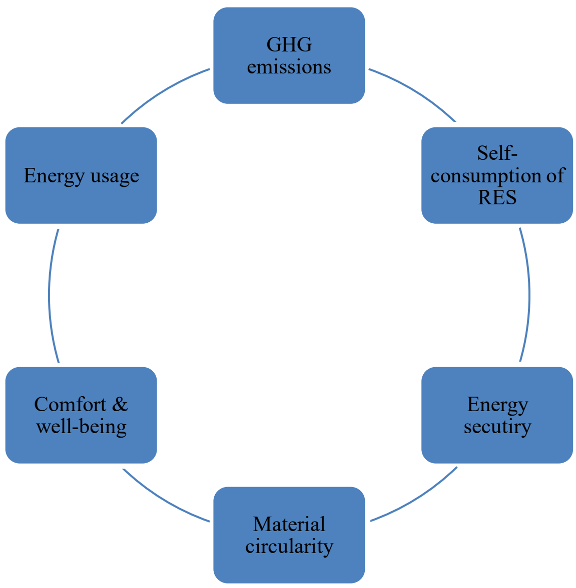


*Figure 41 - The six performance criteria analysed*

These are familiar aspects involving in a performance assessment; it is interesting to focus on material circularity, considering that “the lower the energy consumption in the use phase, the more the construction of the building and the selection of (construction) materials become important while considering the total environmental impacts of building over the entire life cycle." [39]. Moreover, another key point is connected to the quantification of the comfort and well-being improvements by smartness, as underlined in a previous section.

About the activity 2, it is remarked as the choice of the implementation pathway for the SRI assessment is of primarily importance:

a) Linkage of the SRI to the EPC (potentially in a mandatory way);
b) Linkage of the SRI to new buildings and major renovations so that each time a new building/renovation is done it would be a requirement;
c) A market-based voluntary scheme where self-assessment is supported by online tools and 3rd party certified assessment is offered to those willing to pay for it;
d) As c), but with 3rd party assessments supported or subsidized by the state and/or utilities seeking to roll out demand side flexibility, energy efficiency, electromobility, self-generation;
e) Linkage to BACS/TBS deployment trigger points in Art. 14, 15 and 8 of the EPBD;
f) Linkage to smart meter deployment.

Of course, a mandatory and free option increases the uptake of the assessment much more than one which needs to be requested and/or paid. "The more the SRI assessments are conducted, the more than those that procure building technologies and services will wish to know how new smart services will affect their buildings' SRI scores and the impacts it reports on."

In the activity 3 and 4, there is the development and then application of a calculation tool to determine the impacts of the several scenarios, followed by a sensitivity analysis. The SRI deployment, its uptake and investment costs, energy use, GHG emissions, Demand Response and self-consumption, employment both in the energy supply sector and the SRI assessment framework, material circularity, health and well-being, costs and benefits, are at the centre of the modelling and analysis.

Made this overview on the importance and the impacts of the introduction of the SRI assessment, it is clear that now everything done on a sector affects strongly also the other sectors even if not directly involved. The SRI becomes a challenge not only for the built environment; analysing its impacts leads to understand how it would be a great bet to achieve the energy transition goals and improve them on a larger scale.

# 4. Is the data-driven approach the possible solution for a complete building assessment?

***A preliminary analysis of the monitoring and control systems of the Energy Center***

"Monitoring and control" is one of the nine domains involved in the SRI assessment. In the identification of the main features of a smart building, it is necessary to take care of this field and of the possibilities it can offer in terms of response to the needs of the occupants and of the grid, but also in terms of improving the overall performance and energy efficiency. In the context of certifying the performance of an in-use building – which can strongly differ from what is certified in the pre-occupancy phase – the monitoring and control systems have a key role in exploring how the building works when occupied, as well as in investigating possible retrofit measures. As underlined by the interest given to the method C of the SRI assessment as a new kind of interpretation of the Smart Readiness Indicator based on real data, the monitoring system can be fundamental in the perspective of an improved smart building environment.

In this section the focus is not on the possible systems to monitor and control the behaviour of a building and its occupants; the goal here is to directly elaborate the monitored data of the Energy Center, trying to become familiar with the available data and their possible elaboration, also for future activities and objectives.

## 4.1 Monitoring the Energy Center building: the collection of data

In collecting the data, having to deal with a complex building like the Energy Center one, the work is developed around the research of detailed answers to the questions proposed in the figure below, so that at the end of the process, a complete and detailed overview of the most important features of the available data should be known.

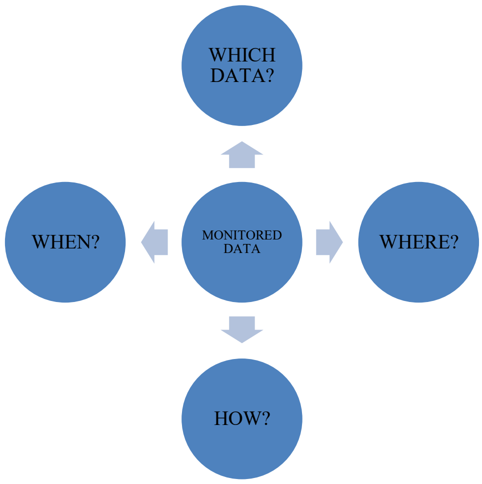


*Figure 42 - Questions to be answered by collecting data*

### 4.1.1 Which data?

This section refers to which data are available, where available means they are monitored and stored, mentioning the parameters of interest for this preliminary analysis:

*Table 11 - About the available data elaborated in the building section*

| BUILDING | |
|---|---|
| **OFFICES**<br>**MEETING ROOMS**<br>AUDITORIUM<br>HALL | $T_{ambient}$<br>$T_{set\ point}$<br>$T_{ext}$ |
| **HVAC SYSTEMS** | $T_{supply}$<br>$T_{return}$<br>$T_{set\ point}$<br>$RH_{supply}$<br>$RH_{return}$ |

*Table 12 - About the available data elaborated in the Thermal side section*

| THERMAL SIDE | |
|---|---|
| **POLYVALENT HEAT PUMP** | **Power**<br>Energy |
| **DISTRICT HEATING** | **Power**<br>Energy |

Other fields available in the platform – concerning the thermal side or also the parameters monitored in the section "plant" – are not considered in this section because not elaborated in my preliminary analysis on the monitoring.

### *4.1.2 When?*

In order to make a coherent study, some information about the operational profile of the building systems are considered:

- plants are switched on at 6 am from Monday to Friday;
- plants are switched off at 19 pm from Monday to Friday;
- for Saturday morning plants are switched on at 6 am and off at 14 pm;
- on Sunday and holidays all the systems are switched off.

Considering that each 15 minutes the values are stored – indoor temperature, temperature of set point, power or energy – a temporal range is chosen according to the availability and my objectives:

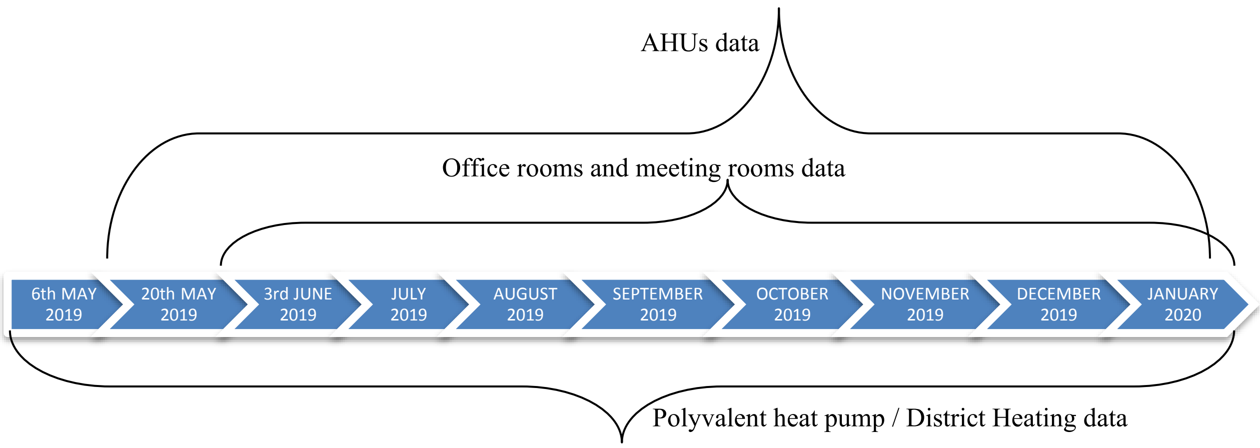


*Figure 43 - Time along which the data of interests are considered for the analysis*

### *4.1.3 Where?*

For the analysis of the ambient temperatures and the relative set points, the idea is to consider strategic rooms, according to the different expositions and different level of occupancy. In the following figures the planimetry of the three floors where offices and meeting rooms are situated are reported, with a focus on the rooms of interests, for which the details of net surface area and level of occupancy are figured out, with:

occupied rooms; meeting rooms; not occupied rooms yet.

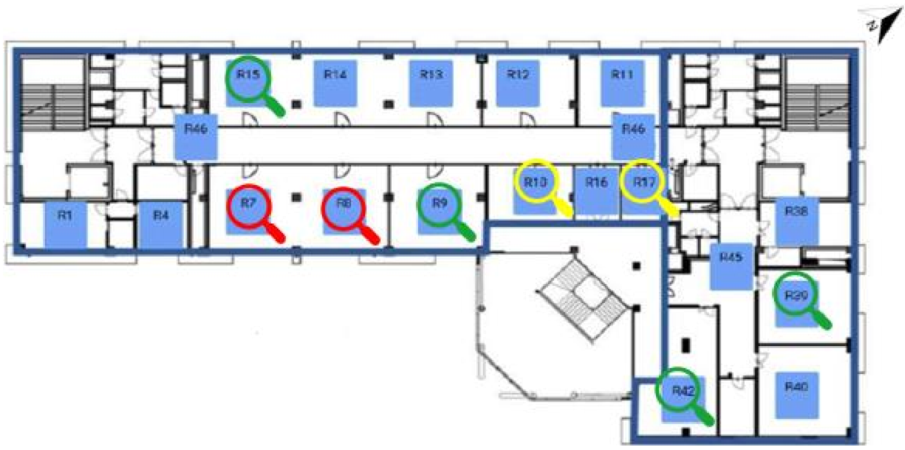


*Figure 44 - 1st floor of EC offices; adapted from Eurix documents*

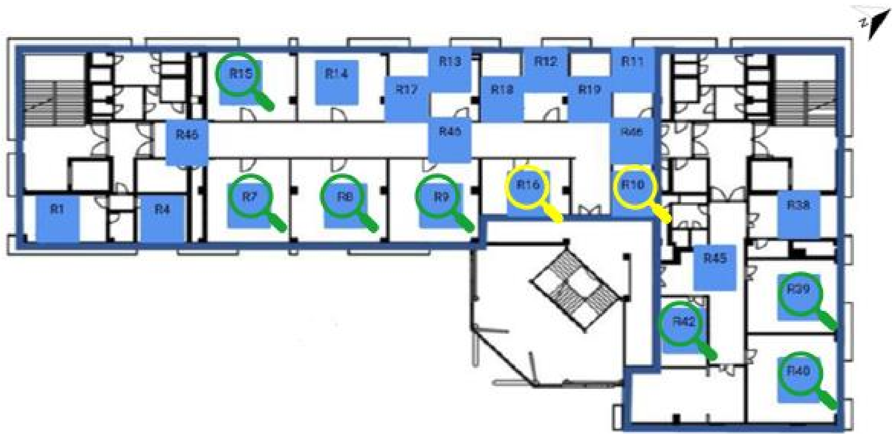


*Figure 45 - 2nd floor of EC offices; adapted from Eurix documents*


*Figure 46 - 3rd floor of EC offices; adapted from Eurix documents*

*Table 13 - Table reporting the list of rooms considered in the data elaboration*

| **EC first floor** | | |
|---|---|---|
| **Room id.** | **Intended use** | **Net floor area [m$^2$]** |
| R7 | not occupied office | 53 |
| R8 | not occupied office | 53 |
| R9 | occupied office | 56.5 |
| R10 | meeting room | 34.5 |
| R15 | occupied office | 45 |
| R17 | meeting room | 16.5 |
| R39 | occupied office | 49 |
| R42 | occupied office | 58.5 |
| **EC second floor** | | |
| **Room id.** | **Intended use** | **Net floor area [m$^2$]** |
| R7 | occupied office | 50.5 |
| R8 | occupied office | 57.5 |
| R9 | occupied office | 54.5 |
| R10 | meeting room | 16.5 |
| R15 | occupied office | 45 |
| R16 | meeting room | 36 |
| R39 | occupied office | 49 |
| R40 | occupied office | 54.5 |
| R42 | occupied office | 26.5 |
| **EC third floor** | | |
| **Room id.** | **Intended use** | **Net floor area [m$^2$]** |
| R7 | occupied office | 53 |
| R8 | not occupied office | 53 |
| R9 | not occupied office | 56.5 |
| R10 | meeting room | 34.5 |

| | | |
|---|---|---|
| R15 | occupied office | 44 |
| R17 | meeting room | 16.5 |
| R39 | occupied office | 49 |
| R42 | occupied office | 58.5 |

*Table 14 - Overview of the chosen rooms*

| | |
|---|---|
| **Total rooms considered** | 25 |
| Rooms with $S_{net} > 40$ m$^2$ | 18 |
| Rooms with $S_{net} < 40$ m$^2$ | 7 |
| Not occupied office rooms | 4 |
| Occupied office rooms | 15 |
| Meeting rooms | 6 |
| | |
| **Total spaces of NW side** | 48 |
| Rooms of the NW side considered | 19 |
| | |
| **Total spaces of NE side** | 15 |
| Rooms of the NW side considered | 6 |

Not only rooms are considered, also the Polyvalent Heat Pump, active in summer, the District Heating, used in winter, and the HVAC systems are taken into account, so in the following figures some details about the plants are shown:

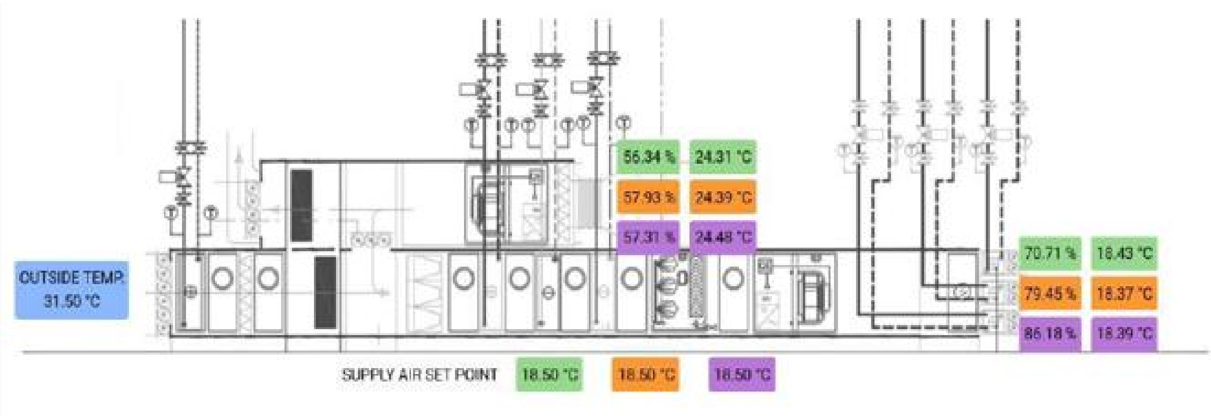


*Figure 47 - HVAC system for NW side, monitoring during a summer day; Eurix documents*

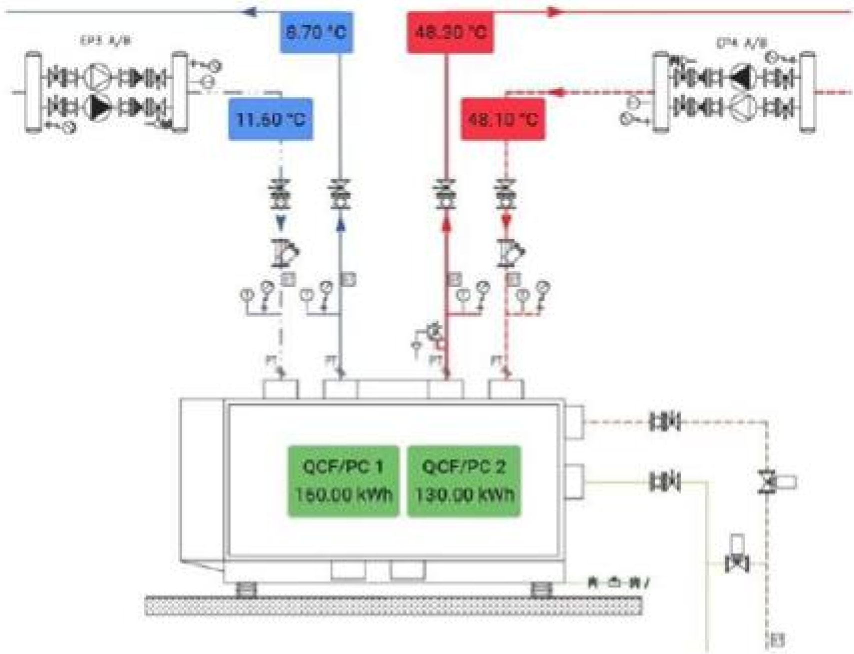


*Figure 48 - Heat Pump, monitoring during a summer day; Eurix documents*

### *4.1.4 How?*

The monitoring system briefly discussed before is developed by Eurix [45], a society hosted in the Energy Center – in the room identified as R9 of the first floor – and it is because of its system of monitoring that there is the possibility in the SRI assessment, for the service "Reporting information regarding heating/cooling/DHW performance", to have an upgrade from level 1 to 2, with "actual values and historical data" now available. All the values reported in the following graphs are taken by the platform made by Eurix in order to store data, available from May 2019. In particular, Eurix exploits some features of its product EOS3 – Energy Operating Saving Cube, related to the monitoring system, about the reading of the data, their historicization and then relative view on the appropriate platform. To do this, Eurix is in communication with the Total Room Automation (TRA) systems installed space by space by Siemens. A TRA potentially can control simultaneously:

1. HVAC,
2. lights,
3. shades.

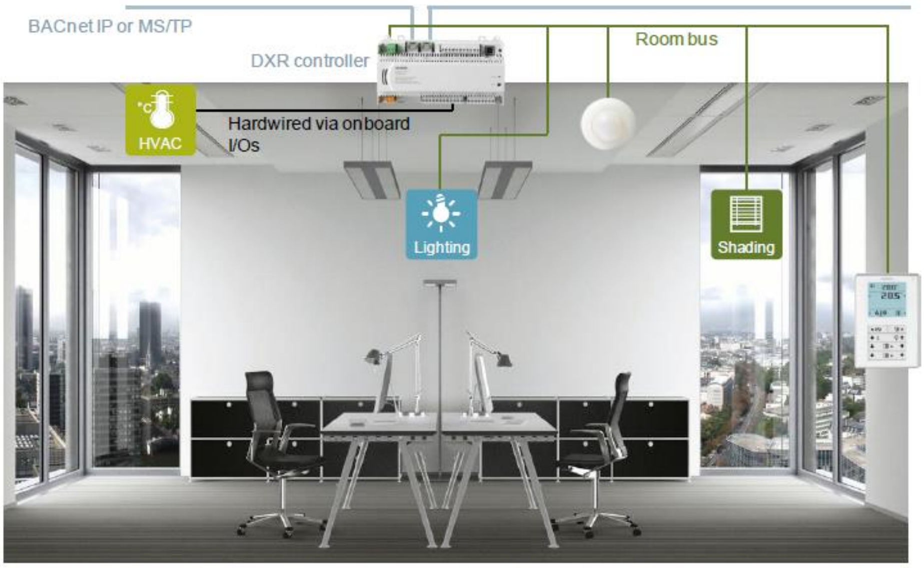


*Figure 49 - TRA overview; Siemens TRA guide [46]*

The TRA guide [46] explains that the common sources of discomfort can be usually a) uncomfortable T, b) poor air quality, c) inadequate lighting, and discusses about how a TRA helps and ensures that adequate temperature can be met and sustained, good air quality is available to keep $CO_2$ concentration at optimal levels, improved lighting is available and kept at a constant level. Having defined the potential management of each room and remembering that up to now the building has not shades or other kind of solar shading systems, the control is assumed to be on the indoor temperature and lighting system, with the occupants acting directly on the system if in a uncomfortable state. Each occupant can decide if increasing or decreasing of 3°C the set point temperature – with respect to a setting obtained by referencing to the outdoor temperature – in order to change the indoor temperature of its space. Moreover, the occupant can "save" its presence in the room so that the lighting system exploits this information, otherwise the lights would switch off in brief time and with a different kind of control. So, what Eurix does is to "talk" with Siemens by an open protocol, BACnet, thanks to which Eurix asks for the data from the available devices. At the moment there is no link with Eurix and the control, in the sense that it is in the Control Room that decisions are taken about how the devices must perform, by Edilog management ("Area Edilizia e Logistica", Politecnico di Torino). Eurix up to now is "a viewer able to save what it sees", but for a future analysis and possible other evaluation an idea can be to exploit all the features of Eurix product, in order to test possibilities of improved performance and energy savings thanks to a more efficient and controlled management, exploring the points of strength and acting on the points of weakness of a new building like the Energy Center one.


*Figure 50 - Eurix product, EOS3 Saving Cube; Eurix [45]*

### *4.1.5 Analysis of the quality of the stored data*

About the overall downloaded data on the Eurix platform, some values are missed, so marked as "null" or not logged:

~ 1.05% of the data about offices and meeting rooms are unavailable;

~ 3% of the required data for the Polyvalent Heat Pump operations are unavailable;

~ 2.45% of the stored data for District Heating are unavailable;

~ 1.25% of the data of the AHUs concerning humidity (NW offices and NE offices) are unavailable;

~ 1.27% of the data of the AHUs about T (NW offices and NE offices) are unavailable.

Talking about missed or unlogged values, it is useful making a comment about the external temperature stored on the monitoring platform. In fact, at the beginning something seemed incoherent with the real values of external temperature so that an external source was used in order to do a comparison and to verify if there were differences, as expected. Data of external temperature of Turin for the months of interest are available on ARPA agency website [47], "Agenzia Regionale per la Protezione Ambientale", referred to the meteorological station based in Via della Consolata, Turin. The values are saved according to hourly aggregation, so working

on a Matlab code, the assumption of fixing the same four values for the four timesteps per hour required is done.
The differences between the meteorological station used at Politecnico are evident:

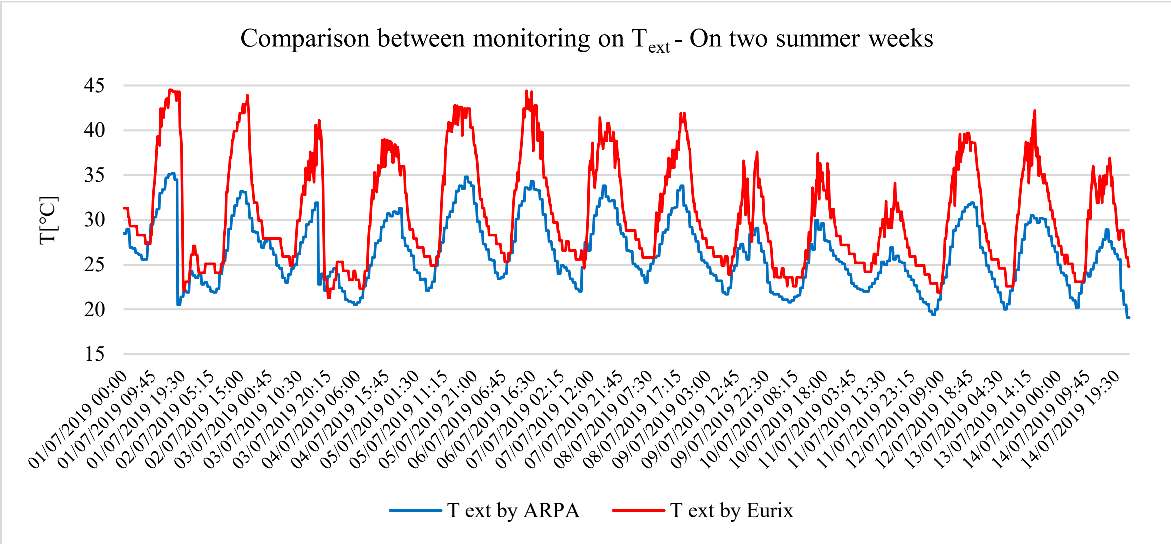


*Figure 51 - Comparison between monitoring on Text over two weeks of July*

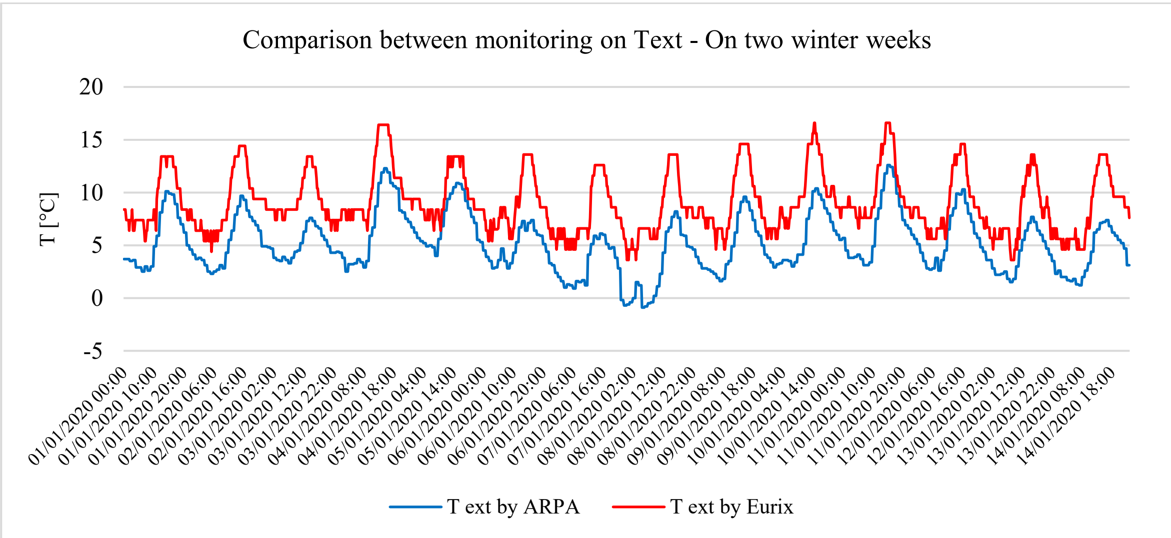


*Figure 52 - Comparison between monitoring on Text over two weeks of January*

For the stored data of ARPA the 0.001% is missed, without taking account the presence of some recorded values but signed with a “*” because of some relative warning comments.

Another point is the one referring to the values of the external Relative Humidity, which are not stored by Eurix, so another external source is exploited, the meteorological station of INRiM Insitute, “Istituto Nazionale di Ricerca Metrologica” [48]. Here data are not based on hourly average but are saved discretely, about two values per hour if the monthly profile is required, so that an elaboration was done is order to make an average hour by hour, saving firstly one value per hour and then having the possibility to quadruplicate this values for the 4 timesteps per hour, which is the level of sub-aggregation chosen on Eurix platform. An example of the available data on INRiM, according to the meteorological station in Turin, is given by the two graphs below, for a period of the cooling season and for one of the heating season.

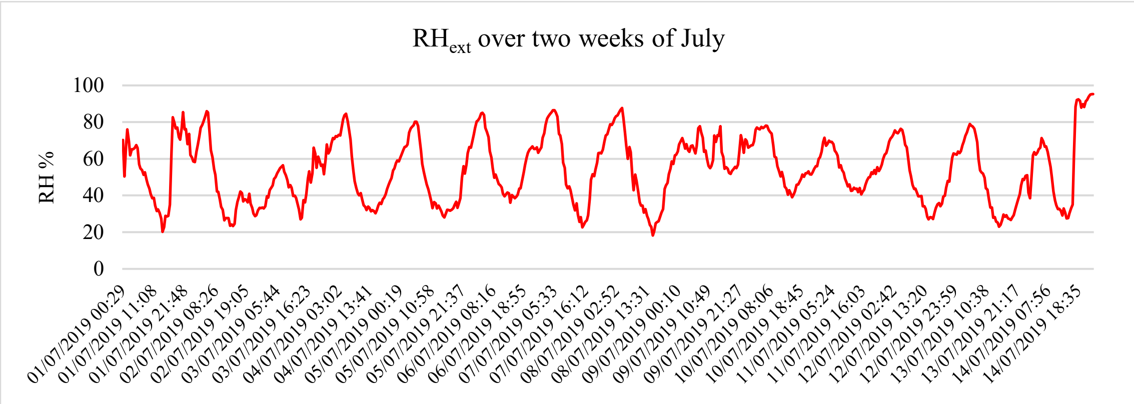


*Figure 53 - RH data for two weeks of the cooling season; INRiM*

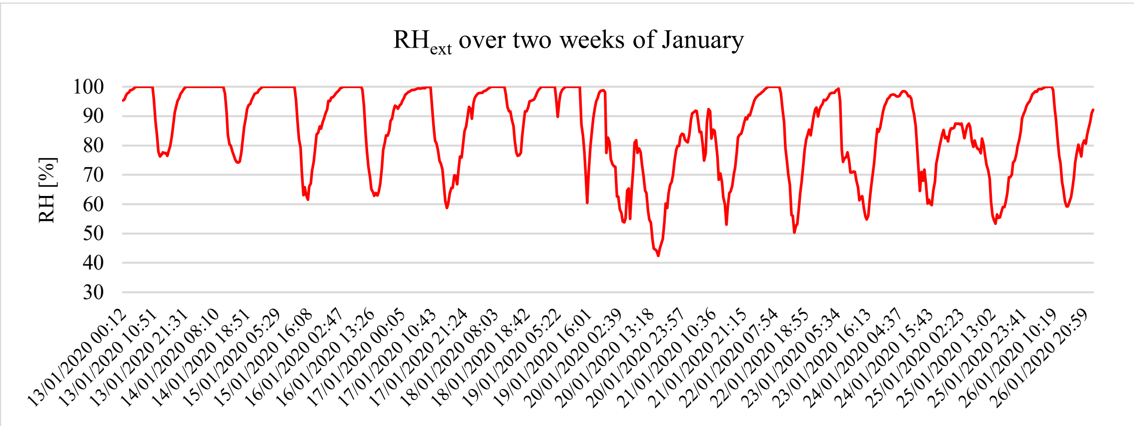


*Figure 54 - RH for two weeks of the heating season; INRiM*

Concerning the data about occupancy, there are not stored info available by Eurix. The point is that each person entering a room can set it on the TRA instrument and in this way the occupant influences the switching of the lights; but after 2 hours the office lights turn off automatically, if no one changes the setting on the TRA or no one is moving in the room for 2 hours entirely. There is not actually a direct measure monitored on the occupancy of a room, even if it can be done with the instruments available in the EC building.

## *4.2 Data stored for the occupied rooms: analysis, comparison and comments*

During the thesis work I elaborated all the data available for the rooms reported in the first section of this chapter, but here only an overview on the analysis and possible future development of the work is taken into account. In this section, it is commented:

a) the office R9 of the 1st floor of the NW side – which hosts the Eurix group;
b) the office R39 of the 2nd floor belonging to the NE side – occupied by EC employees;
c) the room R16 of the 2nd floor of the NW side – used as meeting room.

These rooms are related to different expositions or different intended uses. Moreover, the first two rooms are considered because the involved occupants can be easily interviewed in a future more detailed analysis about their behavior and corresponding parameters of the rooms.

Considering the time period analyzed, here it is chosen to focus on a month, then on two weeks of interest of the months and also with a zoom on a week, for the heating season and the cooling season respectively. The variables stored are plotted, in particular from now on the following plots represent the evolutions of:

- $T_{amb}$: the room temperature,
- $T_{set\ point}$: the set point chosen by occupants during the day,
- $T_{ext}$: the external temperature.

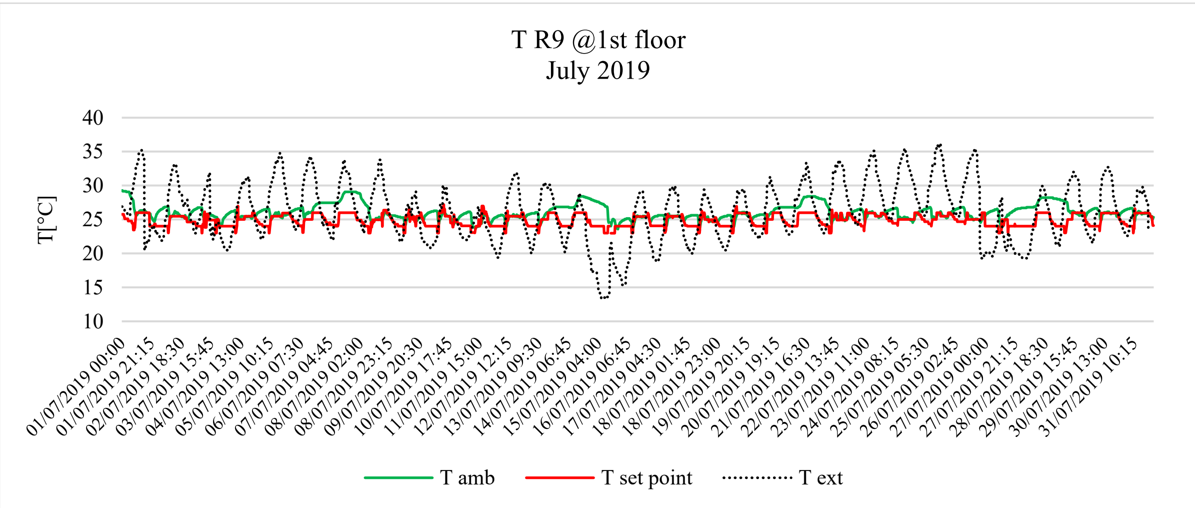


*Figure 55 - T evolution for the office R9 1st floor over July*

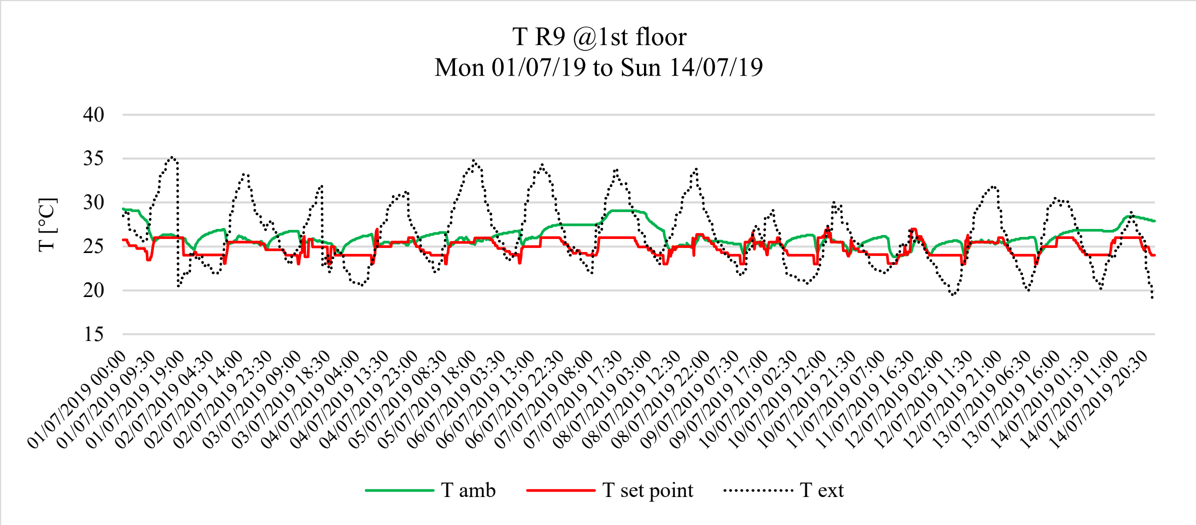


*Figure 56 - T evolution over two weeks of July for R9 1st floor*

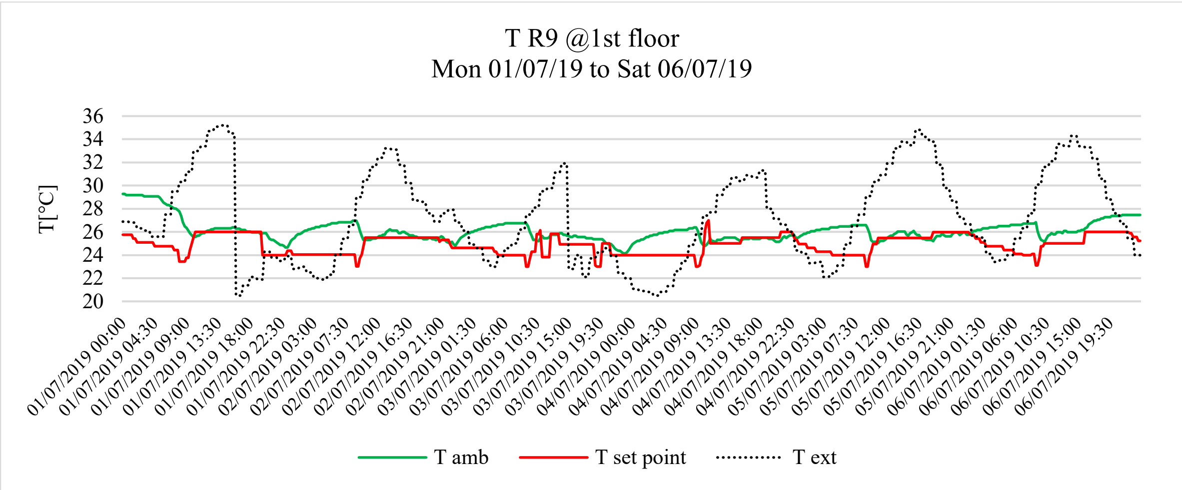


*Figure 57 – T evolution for a week of July for R9 1st floor*

About the cooling season according to the monitored data of the occupied office of the 1st floor, during the working hours the evolution of the indoor temperature seems to be regular, so in line with the set point fixed at 26°C. Of course, something can change during the day because of different set point settings, for instance during the working hours of Wednesday of the week analysed above.

In the next graphs, there are instead some comparisons about what happens for the same days of the cooling season, so with the same external behaviour, but for different rooms:

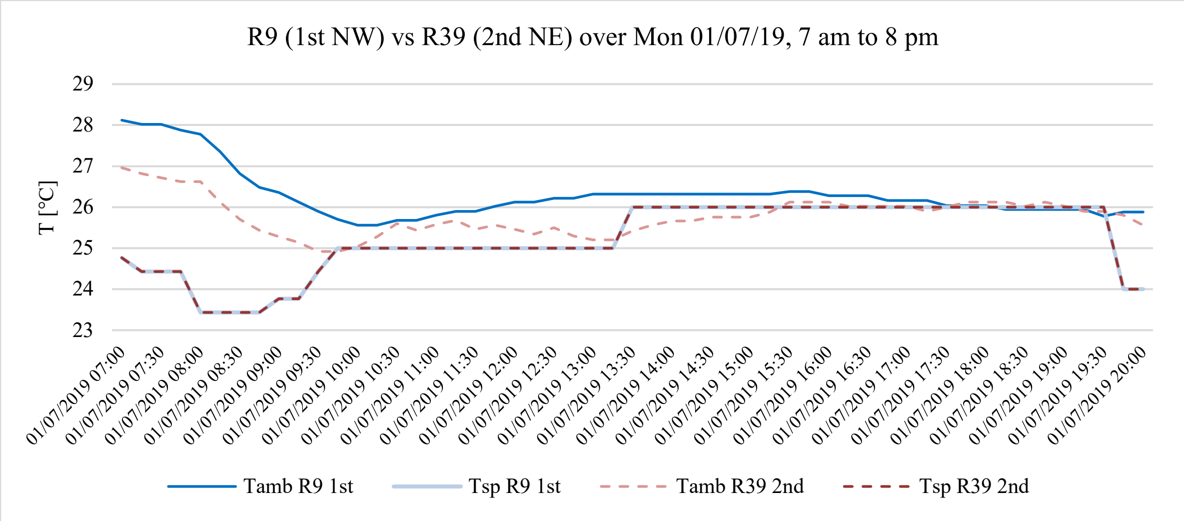


*Figure 58 - Comparison between two occupied rooms in a Monday of July*

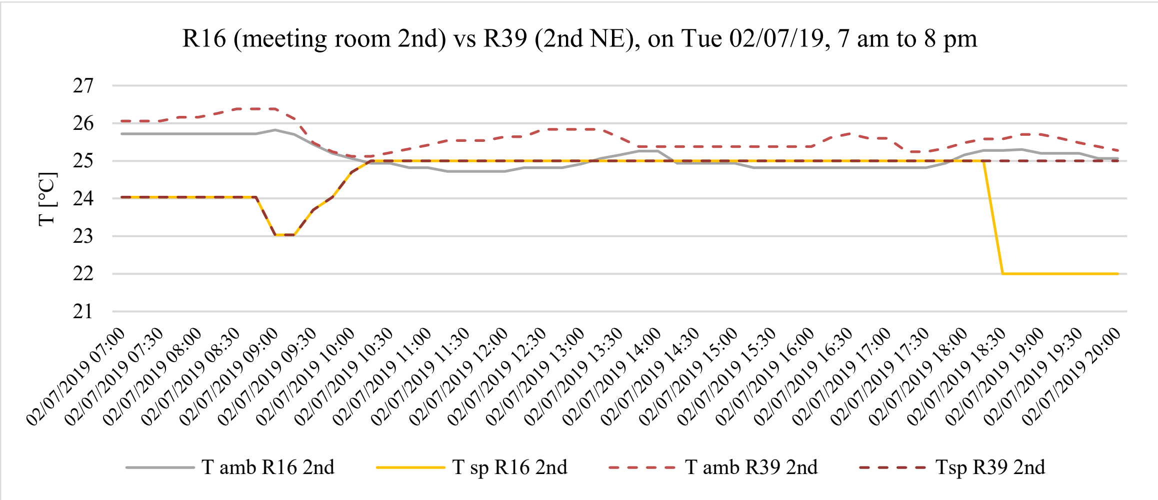


*Figure 59 - Comparison between an occupied office and a meeting room on a day of July*

In fig.58 there is the comparison between two occupied offices – one of the 1st floor NW side and the other of the NE side at the 2nd floor – and in fig.59 between the one of the 1st floor and a meeting room of the 2nd floor (NW side), for the working hours of a day of July. As result, it seems that the set point is the same for the different rooms, but during the day of course the occupant can change it. Nonetheless the same set point, 25°C in the morning and 26°C in the afternoon, the evolution of the indoor temperature is different; the office at 1st floor – mostly for the first part of the day – recorded a $T_{amb}$ higher than 1°C with respect to the one of R39 of the 2nd floor, but during the afternoon both achieved the desirable 26°C. About the meeting room, it is an interesting case because of its intermittency in terms of occupancy; its evolution during the month of July for instance is not so repetitive as it happens for the office rooms.

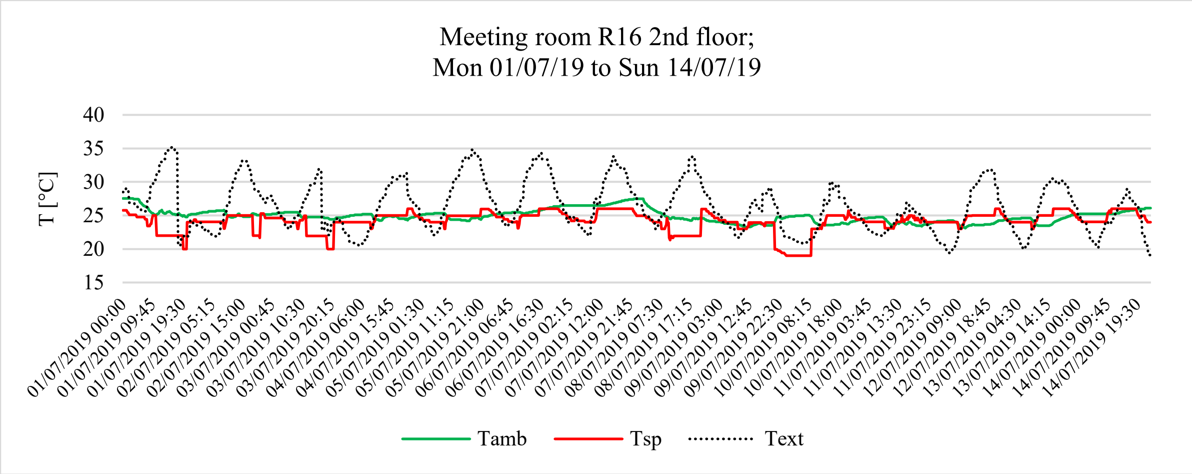


*Figure 60 - T evolution for a meeting room of the 2nd floor, on two weeks of July*

The same elaboration and comments can be done over the heating period, here only some graphs and analysis are reported, as for the cooling season.

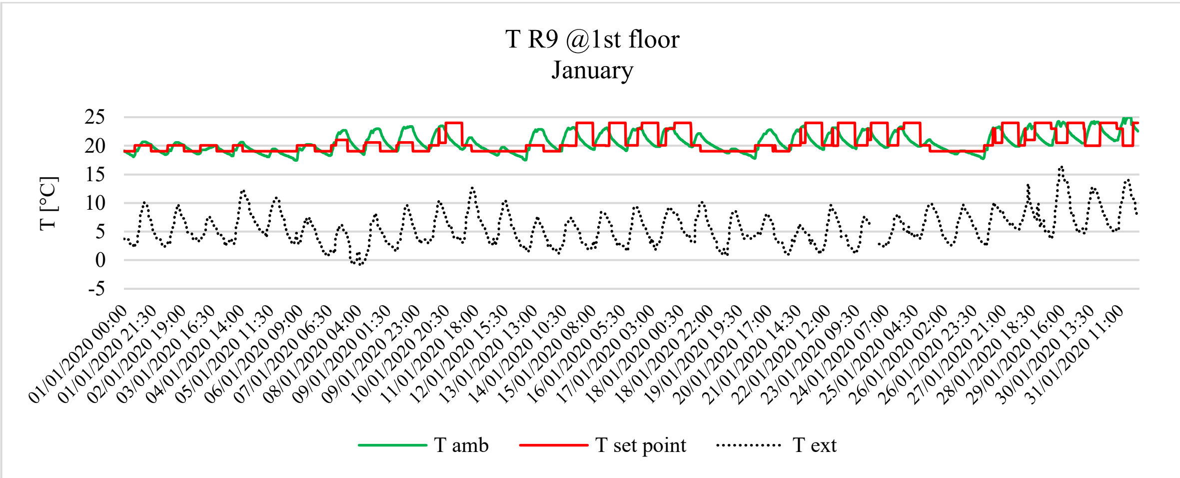


*Figure 61 - T evolution over January for R9 1st floor*

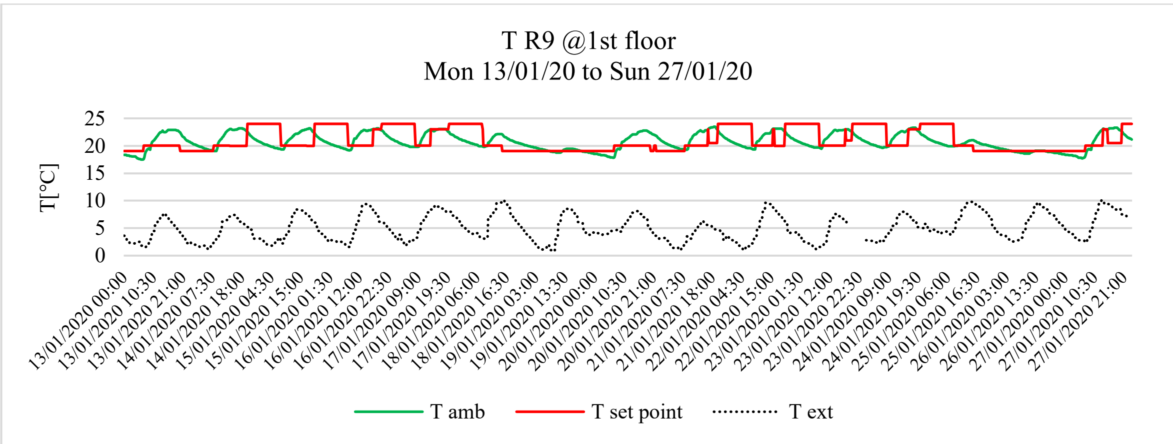


*Figure 62 - T evolution over two weeks of January for R9 1st floor*

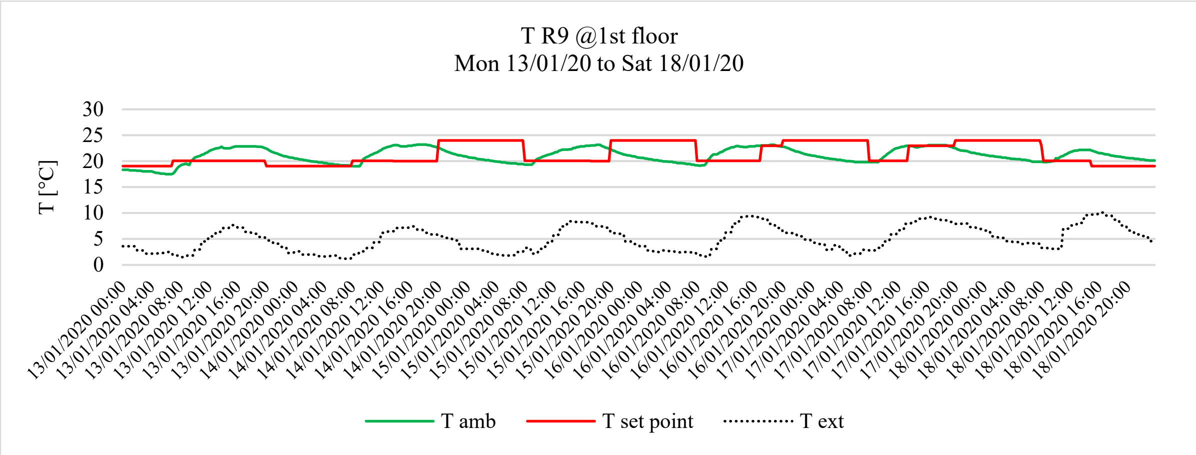


*Figure 63 - T evolution over a week of January for R9 1st floor*

Looking at the graphs above but also at all the other data collected for the heating season, as ordinary behaviour it seems that at 8 am the set point is 20°C until 8 pm. The same is for Saturday from 8 am to 3 pm. However, during the working hours, $T_{amb}$ is quite always higher than the one set, while sometimes it is clear that an occupant is acting to change the indoor condition, as it happened for room R39 of the 2nd floor, where the set point are higher:

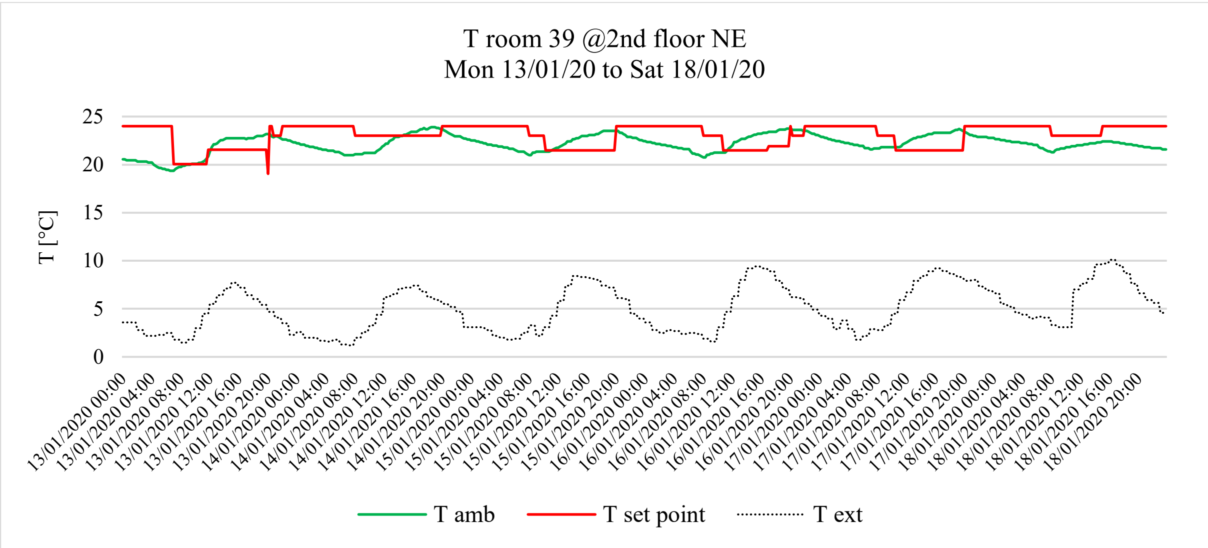


*Figure 64 - T evolution for a week of January for an office room at the NE side of the 2nd floor*

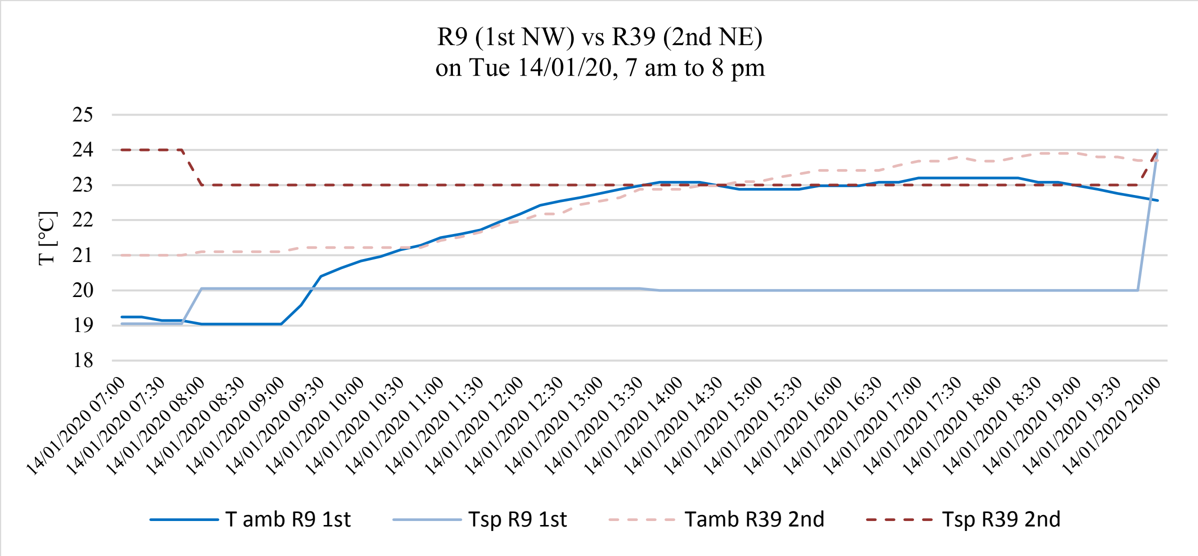


*Figure 65 - Comparison between two occupied rooms over a day of January*

About the working hours, in the plot for comparisons is evident that the set point chosen by the occupants of the room at the NE side of the 2nd floor is 24°C, while the one of the room of the NW side at the 1st floor is set to 20°C for all day long, even if the $T_{amb}$ recorded increases during the day, until 24°C reached in the second half.

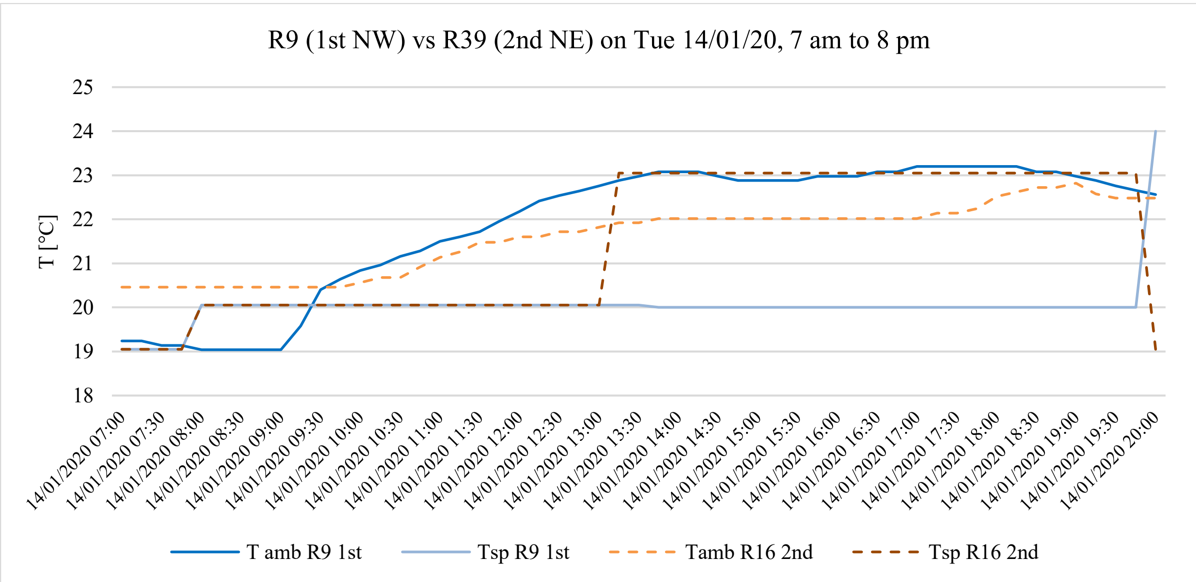


*Figure 66 - Comparison between an office room and a meeting room over a day of January*

The graph above is reported to show a day in which the meeting room R16 2nd floor, differently from some other days analysed and not put under focus, seems to be occupied, having in the second half of this working day of January a set point fixed at 23°C – after a morning with 20°C as default – with a $T_{amb}$ increasing from 20.5°C to 22°C up to 23°C.

These are only few comments about room data and also these are few data showed if compared to the big amount of information collected during this analysis, which is only a first jump into the framework of monitoring and elaboration of data. The idea is to go further to analyse what is available and also to find a way in which to perform a more efficient management. In future there would be the possibility to test a method C for the Smart Readiness Indicator, making use of an advanced monitoring system, starting from this basis. Moreover, these real data can be of interest by focusing on some rooms or some zones in order to validate a dynamic simulation model and to deal with it in reducing the performance gap, towards a general clearer and better knowledge of building and its capability to exploit a dynamic and smart performance.

## *4.3 Monitored data for the building-plant system*

Other material available and of interest regards the HVAC systems in use and the District Heating and Polyvalent Heat Pump. As mentioned in the first section of this chapter – by introducing some plots referred to the Eurix platform and what they record among the used plants in the building – the elaboration of data also focused on the HVAC plants. In particular, I asked Eurix about the presence of the devices able to measure the downloaded data but, as said before, at this moment they are "simply viewer", so it is not their task to manage relative sensors and devices and physically inserting them into the system. So, about AHUs, for instance a great hypothesis could be that the supply sensors are immediately after the separation of conducts for the three floors with offices, for the return instead it is supposed to have the sensors of interest immediately before they assemble again in a unique duct. The graphs reported below are related to the first floor of the NW side, for a week of the cooling season and a week of the heating one, of course it is possible to obtain the same plots for the NE side and for each of the three floors. It takes into analysis the T of supply, return and the T of effective set point for each duct, considering that there is an AHU for each floor of offices. Also, about the AHUs there is the record of the relative humidity, supply and return, for NW side, NE side of first, second and third floor.

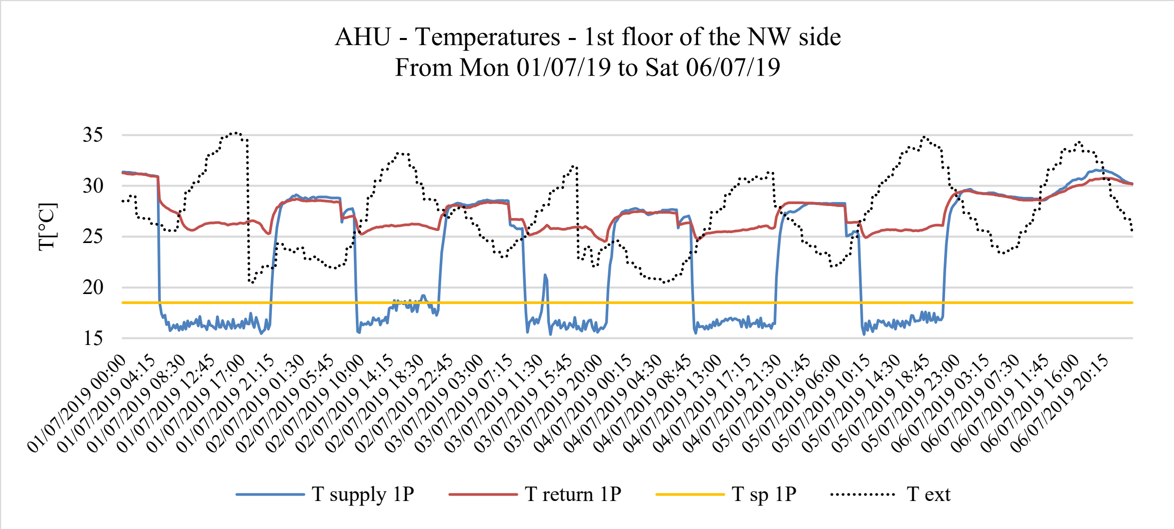


*Figure 67 - T for AHU of the NW side, 1st floor over a week of July*

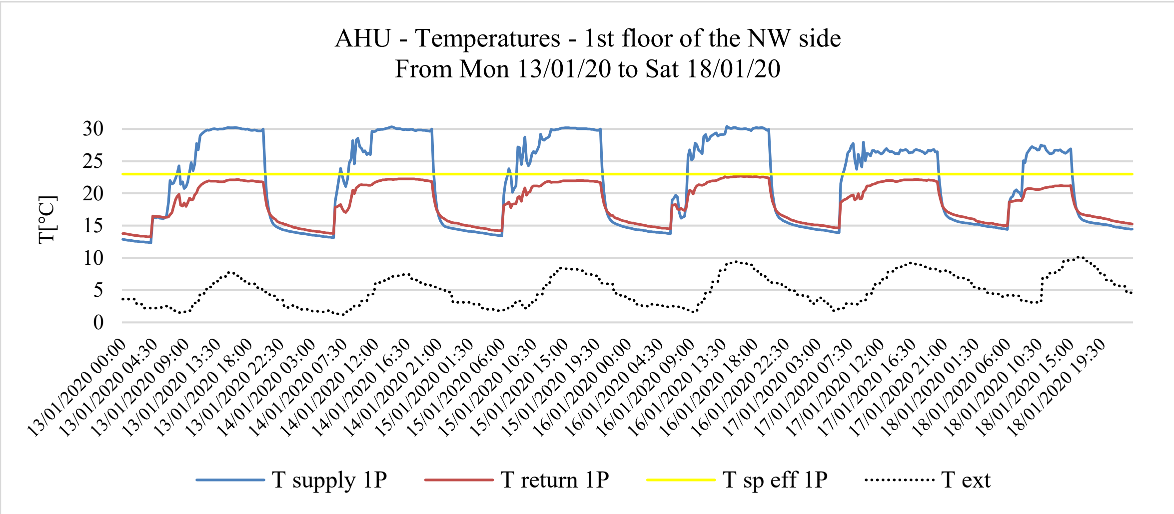


*Figure 68 - T for AHU of the NW side, 1st floor over a week of January*

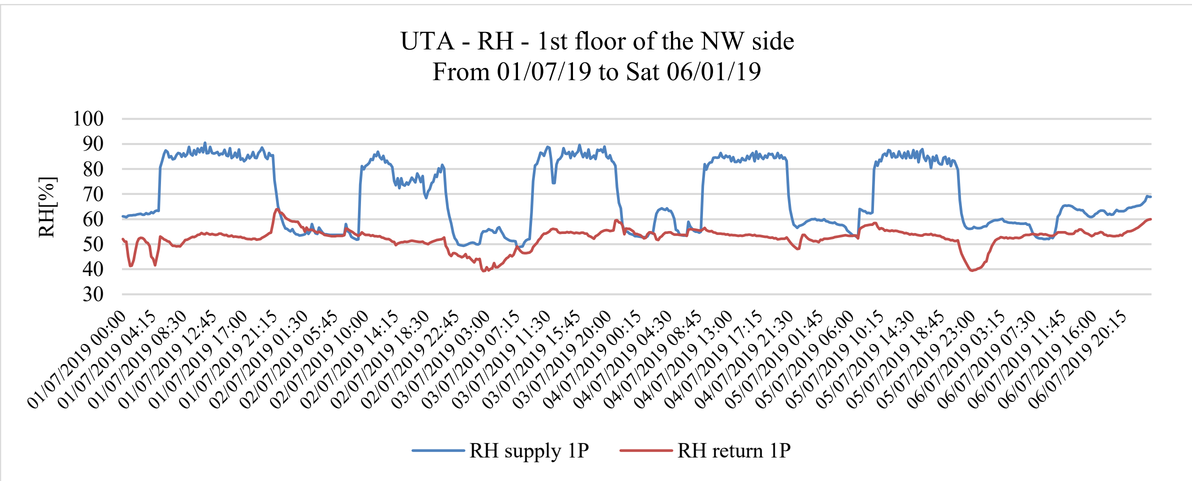


*Figure 69 - Relative Humidity for AHU 1st floor NW, week of July*

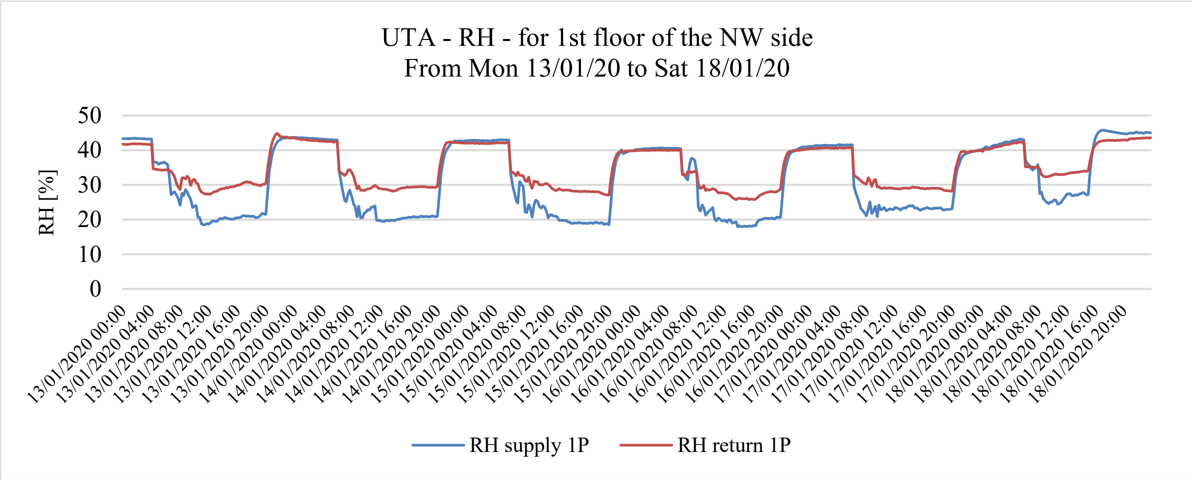


*Figure 70 - Relative Humidity for AHU 1st floor NW, week of January*

The last plots are about the thermal power of District Heating, so concerning the heating season, and the Polyvalent Heat Pump, that up to now is active to satisfy the cooling season needs. Moreover, the Domestic Hot Water needs are now accounted by these plants because there is still no availability of the solar thermal system.

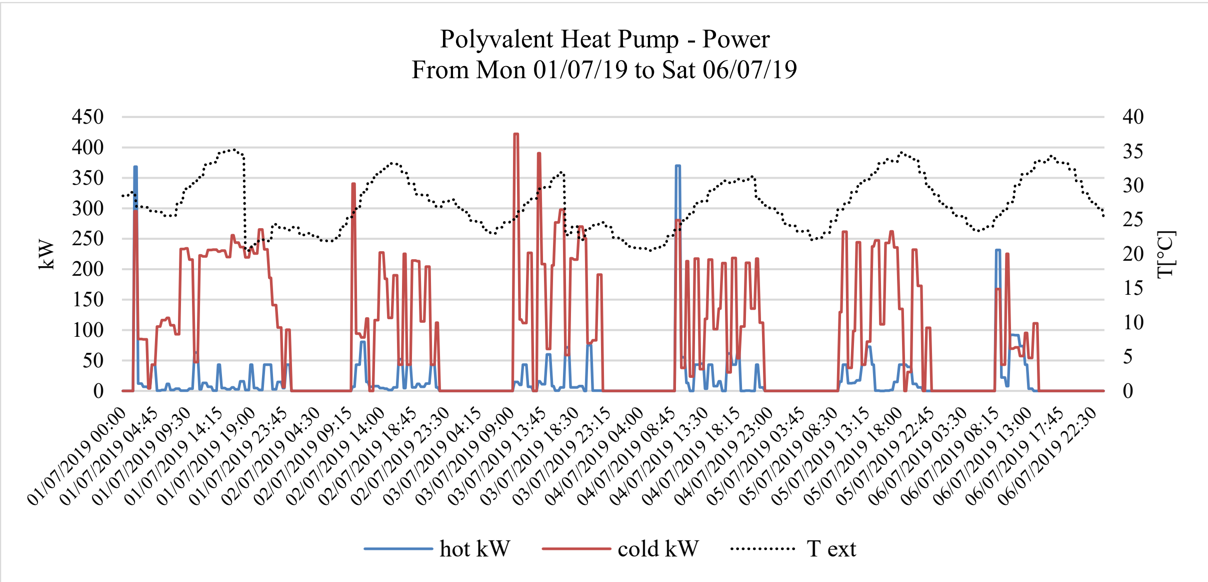


*Figure 71 - Geothermal Heat pump, thermal power evolution over a week of July*

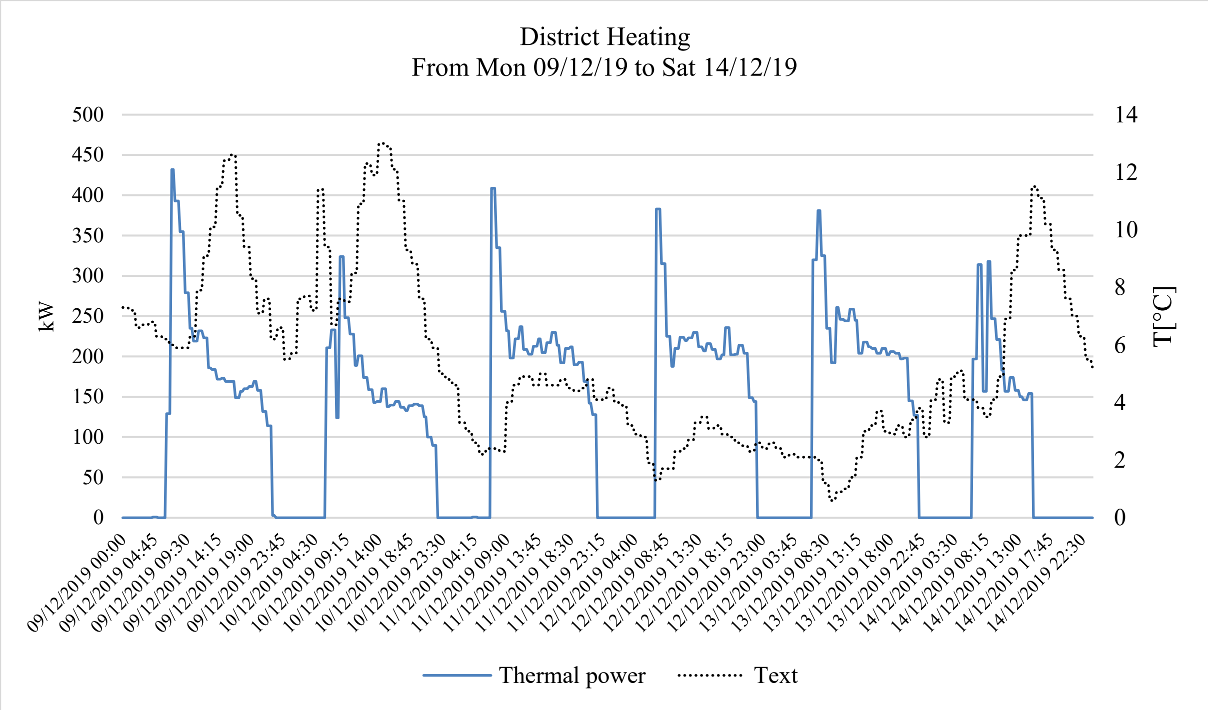


*Figure 72 - District Heating, thermal power over a week of December*

# 5. Is the dynamic simulation modeling a powerful tool to support the smart building assessment?

***The development of a dynamic model for the Energy Center to test if and how the SRI reacts to changes applied to the building components and management***

This third level of knowledge of the Energy Center building deals with the creation of a dynamic simulation model using EnergyPlus software. At this point of the work the purpose is to obtain a validated model in order to check different strategies of control and management. The, the model can be used to test again the SRI, trying to study the sensibility of the Indicator to changes in the model assumptions and its effectiveness in translating a more advanced and smarter building in terms of upgrade of the scores.

In particular, a focus on the dynamic envelope domain and on its possible improvements will allow to comment the Indicator and its real purposes, discussing about the passive design features and how to correctly treat them, in order to satisfy the prerogatives of the SRI assessment and its link with the building energy savings and possible upgrades in performance.

## *5.1 Introduction to EnergyPlus simulation software*

To approach the EnergyPlus simulation tool, an overview on the Building Energy Modeling background is useful, as underlined in the Introduction to the "EnergyPlus Essential" documentation file [49]. According to BEM library [50]: "Building Energy Modeling is the practice of using computer-based simulation software to perform a detailed analysis of a building's energy use and energy-using systems. The simulation software works by enacting a mathematical model that provides an approximate representation of the building. BEM includes whole-building simulation as well as detailed component analysis utilizing specialized software tools that address specific concerns, such as moisture transfer through building materials, daylighting, indoor air quality, natural ventilation, and occupant comfort. BEM offers an alternative approach that encourages customized, integrated design solutions, which offer deeper savings. Using BEM to compare energy-efficiency options directs design decisions prior to construction. It also guides existing building projects to optimize operation or explore retrofit opportunities."

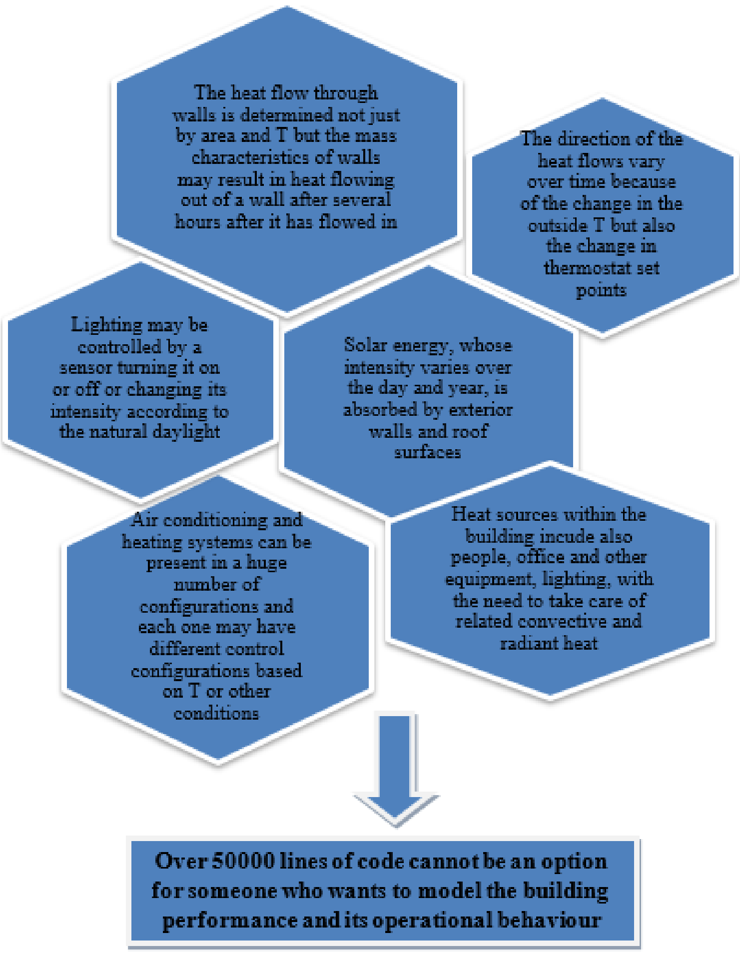


*Figure 73 - Why a model is necessary to understand the whole energy consumption; adapted from EnergyPlus documents [51]*

Focusing on the used simulation tool for the Energy Center building, on EnergyPlus website it is declared that: “EnergyPlus™ is a whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings.” [51].

The general idea is to manage three different key blocks which are strictly interconnected:

1) the Surface Heat Balance which solves the thermal balance referred to surfaces;
2) the Air Heat Balance Manager to simulate the convective and radiant heat transfer;
3) the Building System Simulation Manager which acts on plants, hydronic or non-hydronic.

These modules are part of the Integrated Solution Manager, in which other modules are involved – modularity is the main feature of this simulation tool – with the aim to solve simultaneously all the modules and not subsequentially, because in this way a more realistic and effective simulation model can be obtained.

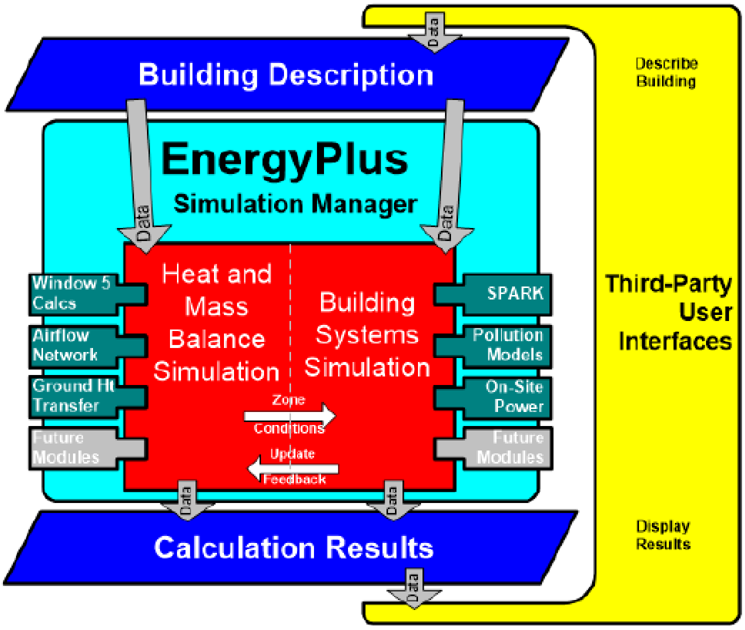


*Figure 74 - "EnergyPlus - the big picture"; "Getting started" EnergyPlus documentation [52]*

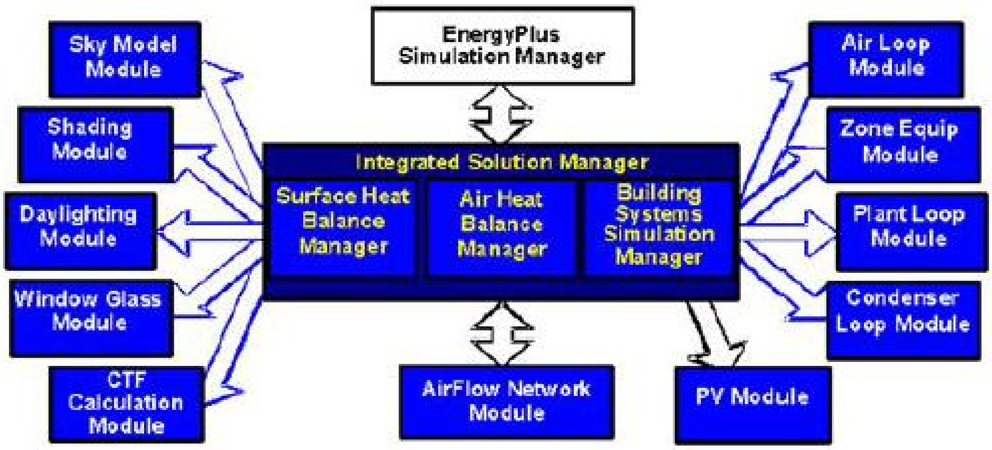


*Figure 75 - "EnergyPlus - Internal elements"; "Getting started" EnergyPlus documentation [52]*

Some of the capabilities of EnergyPlus as simulation tool are deeper summarised in the following table, according to the information collected by the documentation files and the referenced website:

*Table 15 - Overview on main features of EnergyPlus, adapted from EnergyPlus documents [51]*

| INSTRUMENTS | OBJECTIVES |
|---|---|
| Integrated, simultaneous solution of thermal zone conditions and HVAC system response | To simulate unconditioned and under-conditioned spaces, not assuming that the HVAC system can meet zone loads |
| Heat balance-based solution of radiant and convective effects | To produce surface T, thermal comfort and condensation calculations |
| Sub-hourly, user-definable timesteps for interaction between thermal zones and environment, with automatically varied time steps for interactions between thermal zones and HVAC systems | To model systems with fast dynamics while also trading off simulations speed for precision |
| Combined heat and mass transfer model | To account for air movement between zones |
| Advanced fenestration models including controllable window blinds, electrochromic glazing and layer by layer heat balances | To calculate solar energy absorbed by window panels |
| Illuminance and glair calculations | To report visual comfort and driving lighting controls |
| Functional Mockup Interface import and export | For co-simulations with other engines |
| Standard summary and detailed output reports as well as user definable reports with selectable time resolution from annual to sub-hourly, all with energy source multipliers | |
| ASCII text-based weather, input, output files that include hourly or sub-hourly environmental conditions and standard and user definable reports, respectively | |

| | |
|---|---|
| Transient heat conduction through building elements such as walls, roofs, floors etc. using conduction transfer functions | |
| Thermal comfort models based on activity, inside dry-bulb T, humidity etc. | |
| Anisotropic sky model | For improved calculation of diffused solar on tilted surfaces |
| Atmospheric pollution calculations | To predict $CO_2$, CO, $SO_x$, $NO_x$, PM and hydrocarbon production for both on-site and remote energy conversion |
| EnergyPlus can be used for building load calculations and sizing equipment and uses the heat balance method recommended in the ASHRAE Handbook Fundamentals | |

Talking about the weather file input, EnergyPlus needs an ascii file containing the hourly or sub-hourly weather data needed by the simulation program. In the following figure there is the wide range of weather files available for many locations in the world. Find the right place for the building to be simulated is a crucial step and sometimes it can be a challenge.


*Figure 76 - EnergyPlus.net weather file locations; "EnergyPlus Essentials" document [49]*

## *5.2 EnergyPlus to simulate the Energy Center case study: model assumptions*

EnergyPlus is an open source, so that all the source code is available to inspect and modify. The version used for the thesis objective is the 9.2.0 released by DOE in the second half of 2019.

### *5.2.1 The basic geometry rules, the Weather File Data and the assessment of the thermal zones*

As reported in the chapter 2 in relation to the Energy Center building, it is not an ordinary case study; the development of a geometric model as realistic as possible requires a detailed knowledge of it; due to the complexity of the structure, having also to consider a basement area, a ground floor, a mezzanine level and three floors for offices and meeting rooms, some simplifications are done.

First of all, the field "Buildings" needs to be filled, so the details about site are introduced in the model, taking care of the "Geometry Rules":

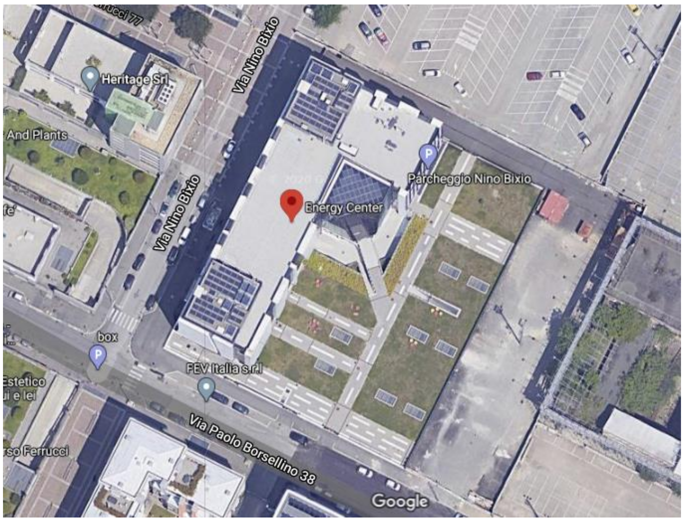


*Figure 77 - Site location; Google*

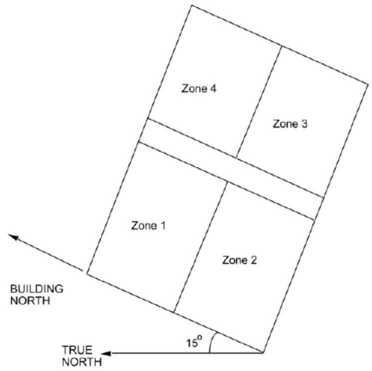


*Figure 78 - Illustration of building North axis setting; "Input Output reference" EnergyPlus document [53]*

Having defined the location setting, another important first input is the one related to the Weather file data; the source of the file is the IWEC, International Weather Energy Calculations. "The IWEC data files are "typical" weather files suitable for use with building energy simulation programs for 227 locations outside the USA and Canada. All 227 locations in the IWEC data set are available for download in EnergyPlus weather format. The files are derived from up to 18 years (1982-1999 for most stations) of DATSAV3 hourly weather data originally archived at the U.S. National Climatic Data Center. The weather data is supplemented by solar radiation estimated on an hourly basis from earth-sun geometry and hourly weather elements, particularly cloud amount information. The reference for the IWEC is: "ASHRAE. 2001. International Weather for Energy Calculations (IWEC Weather Files) User's Manual and CD-ROM, Atlanta: ASHRAE." [51]. Another option available for Turin location is the Italian Climatic data collection "Gianni De Giorgio"; "developed for use in simulating renewable energy technologies, this set of 66 weather files is based on a 1951-1970 period of record. The data were created by Professor Livio Mazzarella, Politecnico di Milano, and it is named in honour of Gianni de Giorgio." [51]. The first mentioned file is the one used, Torino 160590 IWEC. Moreover, there is a third possibility found on *climate.onebuilding.org*, a website from the creators of the EPW (EnergyPlus Weather file data); it is a repository of free climate data for building performance simulation. In particular, "the site contains climate data designed specifically to support building simulations. As such, the files are Typical Meteorological Years (TMY) and are published by a variety of organizations. $TMY_x$ dataset are created by the authors of the website and are derived from hourly weather data through 2018 in the ISD (US NOAA's Integrated Surface Database) using the TMY/ISO 15927-4:2005 methodologies. Currently, there are more than 13550 $TMY_x$ locations supplied. There may be two $TMY_x$ files for a location: a) with data used derived from the entire applicable period, b) with data used derived from the most recent 15 years (2003-2017)." [54]. For Turin, two location sites are available, Torino Bric. della Croce e Torino Caselle. In particular, a new simulation data set based on the update of March 2019 is available for Turin locations.

Focusing the attention on the geometry, the options for setting the right coordinates for the several zones of the building are: a) vertex by vertex, because there is no graphical interface as input on EnergyPlus, b) SketchUp with Open Studio tool to simpler draw the building and then export the geometry on EnergyPlus, c) Design Builder software to obtain the data to be exported on EnergyPlus. The first way was adopted; I created the structure vertex by vertex on EnergyPlus, so that the choice of the thermal zones became essential in defining the spaces. The thermal zones identified are 41 and Sketchup was used at the beginning of the project to have a first general geometric view of what to be built, as explained by the figure below:

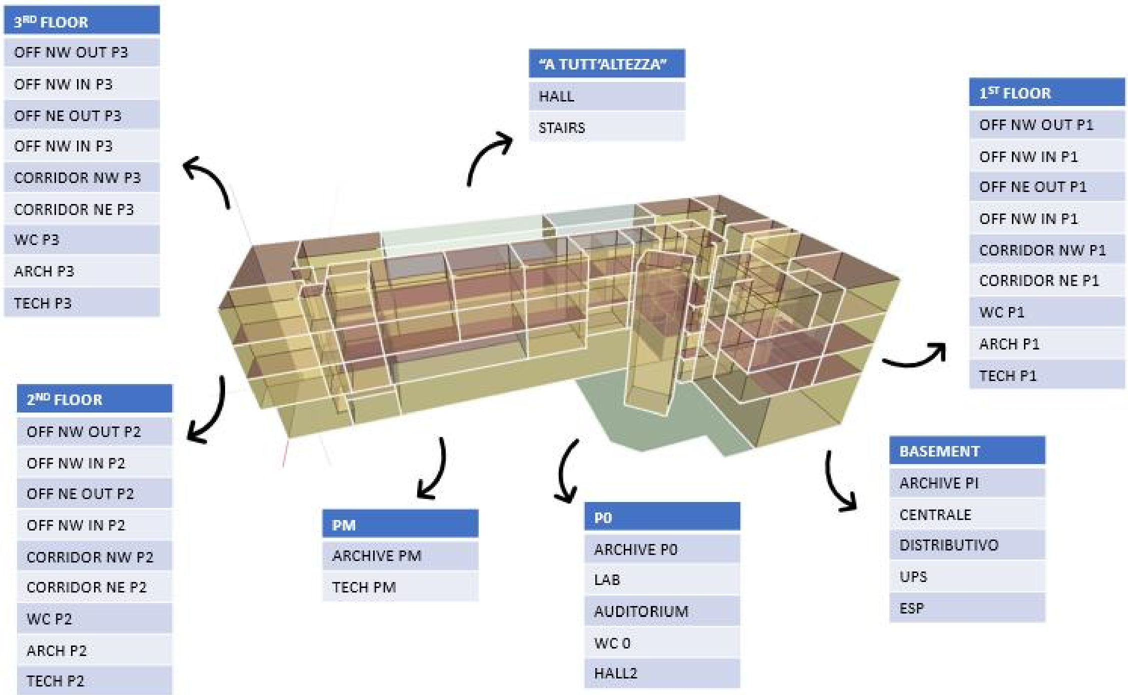


*Figure 79 - The 41 zones identified, view on Sketchup*

The main idea is to distinguish the thermal zones considering the intended use of the spaces, their air conditioning settings, their locations and expositions:

- For each floor, 4 thermal zones of offices are identified, taking care of the NW and NE side and then for each of them of the different expositions. In particular, for the offices of the NW side (the longest one) "out" means that the windows to the outdoor are exposed to NW, while "in" means that the exposition is to the SE. For the offices of the NE side, "out" means that the windows to the outdoor have a NE exposition, while "in" is for the SW for the external windows present. Moreover, there is no distinction between offices and meeting rooms, which are assumed to be normal offices at this point of the modeling. So, 12 zones including all the offices and meeting rooms are defined, 2 per each side, 4 per floor.

- There are corridors separating the “in” and “out” offices areas; the distinction of corridors is done taking care of the floor and the side (NW, NE). So, 6 zones for corridors, 2 per floor, are defined.
- For the auditorium, a proper thermal zone is defined. The same is done for the laboratory.
- The archives include the no conditioned spaces, so all the small rooms which are not occupied by people but available for services.
- The technical rooms are instead small conditioned spaces of the 1$^{st}$, 2$^{nd}$ and 3$^{rd}$ floors.
- In addition, there is the technical room at the mezzanine level which corresponds to a unique thermal zone and also the specular room at the mezzanine level on the other side which is defined as the PM archive – so belonging to the thermal zone related to the archives.
- About WC, there are three spaces per floor used as services, but for each floor a unique zone is defined involving all the spaces of WC1 and WC2 – of the NW side with “out” exposition – and WC3 (inner corner among NW and NE sides).
- For the hall it is assumed a unique space going from the base floor to the third one, the stairs are also developed from the basement to the upper floor.
- About the basement, it is a particular space whose intended use changes according to the development of the several activities of the Energy Center, so that I modelled only the information related to the conditioning and not conditioning spaces, considering that for sure the exhibition area and WC are conditioned and also the UPS room, while the spaces for plants and other services are not.

In doing this subdivision, the air shafts and filters were not taken into account, but considered as part of the adjacent zones.

Chosen the “vertex by vertex method”, it is important to define the building surfaces dimensions; as reported in both documents “EnergyPlus Essentials” [49] and “Tips and Tricks Using EnergyPlus” [55]. In fact, about the wall thickness, “when describing the geometry of building surfaces in EnergyPlus, all surfaces are a thin plane without any thickness. The thickness property of the materials which are assigned to the building surface are only used for heat conduction and thermal mass calculations.” In this model it is assumed as dimensions that for interior walls the middle is considered and for the exterior walls the inside one. In this way, exterior heat transfer areas are maintained, compensating thermal bridges and the model geometry is coherent. Then, zone areas and volumes – in particular the height of the zones - can be imposed in the related zone objects.

In the following figure there is the output of the geometric model obtained on AutoCAD after running the simulation; everything is coherent with the assumptions done at the beginning.

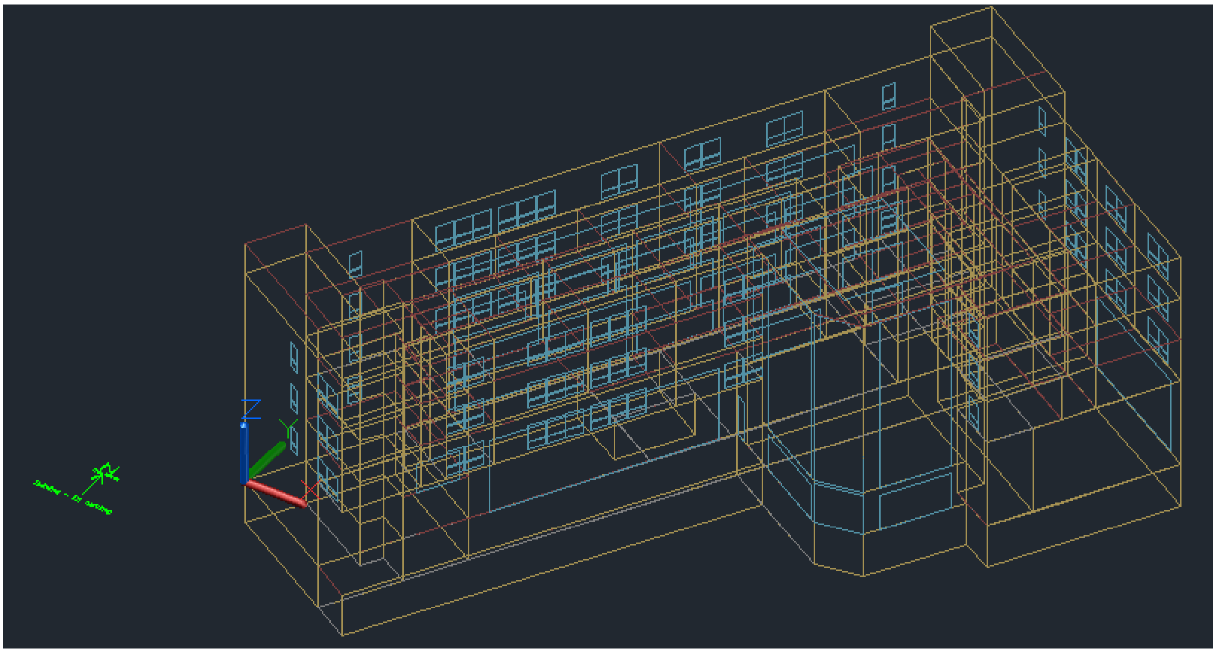

*Figure 80 - The EC final geometric output on AutoCAD*

About the basement, it is assumed that no windows are present, even if in the reality there are fenestration surfaces but here this floor was simply created to give the right boundary conditions to the ground floor and the basement. Finally, about the overall conditioned surfaces, the assumptions give a model in line with the one of the technical scheme, always taking care of the fact that there are some assumptions made but that respect at the same time the general features of the building.

### *5.2.2 The materials chosen for the opaque and transparent envelope*

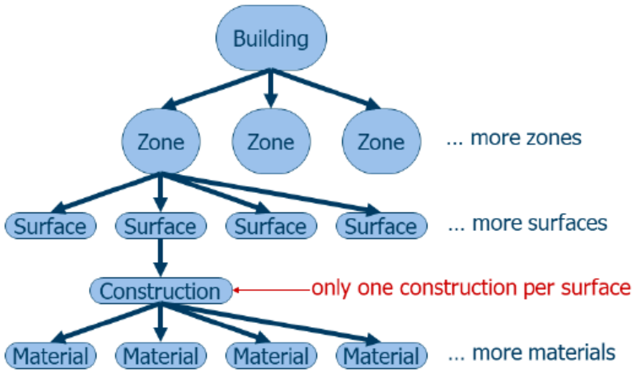


*Figure 81 - Envelope component hierarchy; "EnergyPlus Essentials" document [49]*

In the figure above it is better clarified how to proceed in the definition of the zones, in terms of constructions and relative materials. An important rule of EnergyPlus is that only one single construction can be addressed to a surface, while at maximum 10 layers, in order from the outside to the inner layer, listed to define the construction. To add the proper materials used for the Energy Center building walls, floors and ceilings the information from "LEGGE 9 gennaio 1991, n.10; RELAZIONE TECNICA; D.Lgs. 29 dicembre 2006, n. 311 - ALLEGATO E; D.P.R. 2 aprile 2009, n. 59" are considered, where the Edilclima software is used, and also some details are taken from the other documents of relevance during the project phase. Firstly, the properties of the materials composing the layers are added (thickness, conductivity, density etc.) and then the identified materials are put into the related construction object.

Since the Energy Center is a new and complex building and – as it is also clear with a first view – the area occupied by glazed surfaces is considerable; it becomes important to deeply focus on windows in order to have a model in line with the real building energy performance.

In the following table the most important properties of the opaque exteriors and fenestration surfaces are shown:

*Table 16 - Main properties of opaque exterior and glasses used*

| OPAQUE EXTERIOR | U WITH FILM [W/(m$^2$K)] | |
|---|---|---|
| M62 DRYWALL WITH FINISCHING IN STEEL | 0.136 | |
| M122 CONCRETE BLOCKS CON CAPPOTTO | 0.215 | |
| M63 DRYWALL WITH GLASS FINISCHING | 0.136 | |

| | | |
|---|---|---|
| M64 DRYWALL WITH FINISHING IN OPAQUE PANELS | 0.202 | |
| M33 OPAQUE EXTERIOR WITH OPAQUE GLASS - NW | 0.196 | |
| M124 OPAQUE EXTERIOR BLIND FACADE - SE | 0.222 | |
| M66 OPAQUE EXTERIOR WITH FINISHING IN STEEL | 0.192 | |
| S1 ON TERRACE | 0.194 | |
| S2 ON TERRACE | 0.176 | |
| P31 ON PORTICO | 0.178 | |
| P52 FLOOR | 0.277 | |
| | | |
| **FENESTRATION SURFACE** | **GLASS U-FACTOR [W/(m$^2$K)]** | **SHGC [-]** |
| FACADE "A CELLULE" | 1.17 | 0.34 |
| GLASS COVERAGE ON HALL | 1.88 | 0.59 |

Even if there is a photovoltaic present in the real building, at this stage of the model it is developed as a series of windows with the same stratification proposed for the others; in fact, all the fenestration surfaces were modelled in the same way, and frames and dividers inserted when required. Also, the fenestration coverage over the hall, where in the real building photovoltaic cells are installed, was modelled as a window coverage with the same materials of the others.

### *5.2.3 The "Schedule: Compact" option and other settings*

An important point for the simulation process is to assess schedules of many items, for instance related to the occupancy density, the set point of the thermostats and their control, the lighting and equipment systems use etc. The "one fell swoop" option is used, using the "Schedule: Compact" field. By adding objects here, all the features of the schedule components are accessed in a single command; the requirement is to cover all the days of the year, as for the other optional pathways for scheduling.

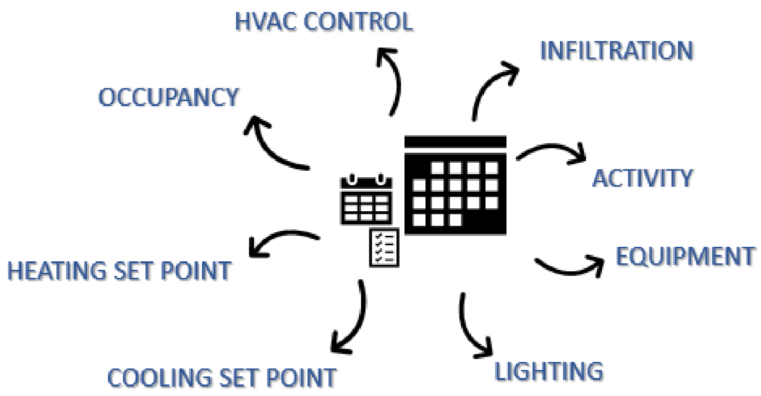


*Figure 82 - What is scheduled*

In the fig.87 the main areas of interests for scheduling are reported. First of all, it is taken into account that the Energy Center building is closed on Saturday afternoon and Sunday. Knowing this, to make a correct setting it is necessary to consider the available rules and regulations to give the right schedules when occupants are in. In particular, the following regulations are used in the model, after a deep focus on them and the analysis of values of interest, in some cases compared before making a choice:

- UNI 13390:1995, "Impianti aeraulici ai fini di benessere"
- UNI EN ISO 7730:2006, "Thermal comfort in buildings"
- ISO 18523-1:2016, "Energy performance of buildings - Schedule and condition of building, zone and space usage for energy calculation Non-residential buildings"
- UNI EN 16798-1:2019, "Energy Performance of buildings – Ventilation for buildings – Part 1".

Focusing on the set point temperature, for each room there is a proper setting, but the same temperature is proposed for each zone, so that 20°C is the set point for the occupied hours during the heating season and 26°C for the cooling season. In particular, only for WC zones and Laboratory, the Single Heating Thermostat is set.

### *5.2.4 The Ideal Loads Air System and model calibration*

In order to investigate the link between the energy needs and possible savings of a building and the Smart Readiness Indicator, the objective of this preliminary dynamic model is to get the energy needs for the heating and cooling season, so still before introducing the complexity of the plant systems and more detailed management options. According to this, the Ideal Loads

Air System was applied to this first simple model of the Energy Center building; it means that there is no need to specify air loops, water loops etc., all that it is needed are the zone controls, zone equipment configurations and the ideal loads system components. This object in fact is described as an ideal unit mixing air at the zone exhaust condition with the specific amount of outdoor air and then adds or removes heat and moisture at 100% efficiency in order to produce a supply air stream at the specified conditions. Setting the Equipment Lists for the Ideal Loads, the correct schedules and values for internal gains, then also assuming the natural ventilation to guarantee the changes per hour proposed in the technical relation, the simulation run and among the output files the required needs appear as "District Heating" and District Cooling", to be compared with the kWh found in the document of the building project, where Edilclima is used – by simulating a quasi-stationary method according to the UNI/TS 11300-1.

*Table 17 – EnergyPlus vs Edilclima: energy needs outputs*

| MODEL | HEATING ENERGY NEEDS [kWh/y] | COOLING ENERGY NEEDS [kWh/y] |
|---|---|---|
| ENERGYPLUS | 102’225 | 149’270 |
| Edilclima (project documents) | 102’596 | 144’317 |
| ENERGYPLUS–EDILCLIMA | **-0.36%** | **+3.43%** |

Done this comparison, the preliminary model built up on EnergyPlus can be considered calibrated according to the energy needs calculated for the summer and winter seasons on the technical project documents. This becomes the starting point for the objective of this chapter, which concerning the analysis of different solutions, about physical changes on the envelope but also different control assumptions, in order to test if and how the energy needs of the building and the SRI scores are linked.

## *5.3 Upgrade for the services of the Dynamic Envelope domain and its consequences on the dynamic simulation model and on SRI scores*

The results obtained for the Dynamic Envelope during the testing phase represent a great starting point to adapt some changes to the dynamic simulation model by acting on this domain and to test what it means in terms of the SRI assessment. First of all, it is of relevance considering that a domain like this is not so silly for the non-residential buildings of recent construction, with the fenestration surfaces covering a relevant share of the entire structure, so that it becomes of interest trying to find solutions to improve their performance. The following services proposed by the SRI catalogue are directly taken into account:

*Table 18 - Table reporting the services belonging to DE, adapted from the SRI service catalogue*

| Code | Service group | Smart ready service | Functionality level 0 (as non-smart default) | Functionality level 1 | Functionality level 2 | Functionality level 3 | Functionality level 4 | Preconditions / Dependency on other services or building types |
|---|---|---|---|---|---|---|---|---|
| DE-1 | Window control | Window solar shading control | No sun shading or only manual operation | Motorized operation with manual control | Motorized operation with automatic control based on sensor data | Combined light / blind / HVAC control | Predictive blind control (e.g. based on weather forecast) | Only applicable in case movable shades, screens or blinds are present |
| DE-2 | Window control | Window open/closed control, combined with HVAC system | Manual operation or only fixed windows | Open/closed detection to shut down heating or cooling systems | Level 1 + Automised mechanical window opening based on room sensor data | Level 2 + Centralized coordination of operable windows, e.g. to control free natural night cooling | | |
| DE-4 | Window control | Reporting information regarding performance | No reporting | Position of each product & fault detection | Position of each product & fault detection & predictive maintenance | Position of each product, fault detection, predictive maintenance, real-time sensor data (wind, lux, T…) | Position of each product, fault detection, predictive maintenance, real-time & historical sensor data (wind, lux, T…) | |

Focusing on the table above, the methodology applied consists in the following steps:

1) For the service DE-1 the functionality level 1 is applied to all the fenestration surfaces of the offices and auditorium and laboratory, by introducing four different types of solar shadings and the relative control; energy needs coming from this new input and also the SRI scores are evaluated.
2) For the service DE-1 also the functionality level 2 is introduced, applied the right management of the shading control; the energy needs and the SRI scores belonging to this new model are assessed.

3) For the service DE-1 also the functionality level 3 is applied, simulating in the office rooms of the EnergyPlus model a strategy to take care also of this advanced control solution; again, the energy needs and the SRI scores are analysed.
4) For the DE-2, the functionality level 2 is directly proposed as control on window opening and closing, so that the simulation can run again and with new outputs to be commented with the new SRI scores.
5) Finally, both the best configuration of service DE-1 and DE-2 – where "best" means the one corresponding to the biggest amount of energy savings – are put together to have a final "Dynamic Envelope - improved" simulation model and an overall SRI score supposed to be the highest one obtained at this level of the analysis.

In all the steps the service DE-4 is taken at functionality level 2, considering that in each case it is possible to evaluate the performance of windows and, when present, of the relative solar shadings. Moreover, about the evaluation of the SRI scores in the different scenarios, if the DE-1 is the service under analysis, the DE-2 is considered at 0 and viceversa, in other words the service is "frozen" when the other operates, so that only in the last score evaluated the services are considered both at a level different form the non-smart one.

The savings under focus are those of the cooling season; according to the adopted control strategies, the summer period is the one improved in terms of energy needs.

The dynamic model of the Energy Center on EnergyPlus – as it is now – has no window solar shading control; the service DE-1 is clearly the first to be improved by adding sun shading materials. In order to see the differences in terms of performance among several kinds of window solar shading types, four options are proposed to be introduced as change in the initial energy model:

a) External blinds;
b) Between-glass blinds;
c) Internal blinds;
d) Internal shades.

The first three options consider the same shading material, it is its position in relation to the window that changes. For the internal shades instead, a different material is introduced and in both cases the library of EnergyPlus is used so that the properties are of default ("Blind with medium reflectivity slats", "Medium reflect-medium slats shade"). Having now four different models in which for offices, auditorium and laboratory the solar shadings are added, the simulations have to run according to different strategies of control in line with the functionality levels proposed on the SRI catalogue. In the following steps the service DE-1 relative to the control of the solar shading is taken into account:

- To apply the functionality level 1 to the fenestration surfaces of all the offices, auditorium and laboratory, so to guarantee a manual operation, the idea is to add the occupancy schedule for scheduling the use of the solar shading, simulating the action of the occupants; it is considered that, when the indoor temperature reaches and overcomes the set point of 26°C, the solar shadings are used. Of course, it is an optimal situation, but considering that it is an incontrollable behaviour and complete subjective action, it is a way in which it can be simulated.
- To introduce the functionality level 2, the proposed setting “On if high solar on window” is chosen, so that, if during summer the value of 250 W/m$^2$ over windows is overcome, the solar shadings are shutoff.
- To finally apply the functionality level 3, the control is set again as the functionality level 2 case but also the “glare control” is added; in this way a join control is possible, in order to deploy shading when the solar incidence on window is too high or the glare from the window is too high. This second sentence in terms of the simulation model is translated with the introduction of daylighting controls and reference points for daylighting, leaving the maximum allowable discomfort glare index set to 22 as default.

About the second service, there are some several options in order to manage the opening and closing of windows; here it is chosen to apply directly the second level of functionality by exploiting the free cooling during the unoccupied hours, when the outdoor air temperature is not higher than 25°C.

The following tables and graphs are relative to all the steps explained up to now and their results of relevance; the energy savings of the cooling season obtained because of a smarter management and control are put in evidence, and also the different outcomes from the SRI assessment are reported:

*Table 19 - Cooling energy savings coming from the upgrade of DE-1 in terms of annual MWh*

| ***Application on 50% (the remaining 50% is set to 0) - SAVINGS IN MWh/y*** | | | |
|---|---|---|---|
| | *functionality level 1* | *functionality level 2* | *functionality level 3* |
| *EXTERNAL BLIND* | 9.3 | 18.3 | 20.8 |
| *BETWEEN GLASS BLIND* | 3.7 | 7.3 | 9.5 |
| *INTERNAL BLIND* | 0.8 | 2.0 | 4.3 |
| *INTERNAL SHADE* | 2.3 | 4.2 | 6.5 |

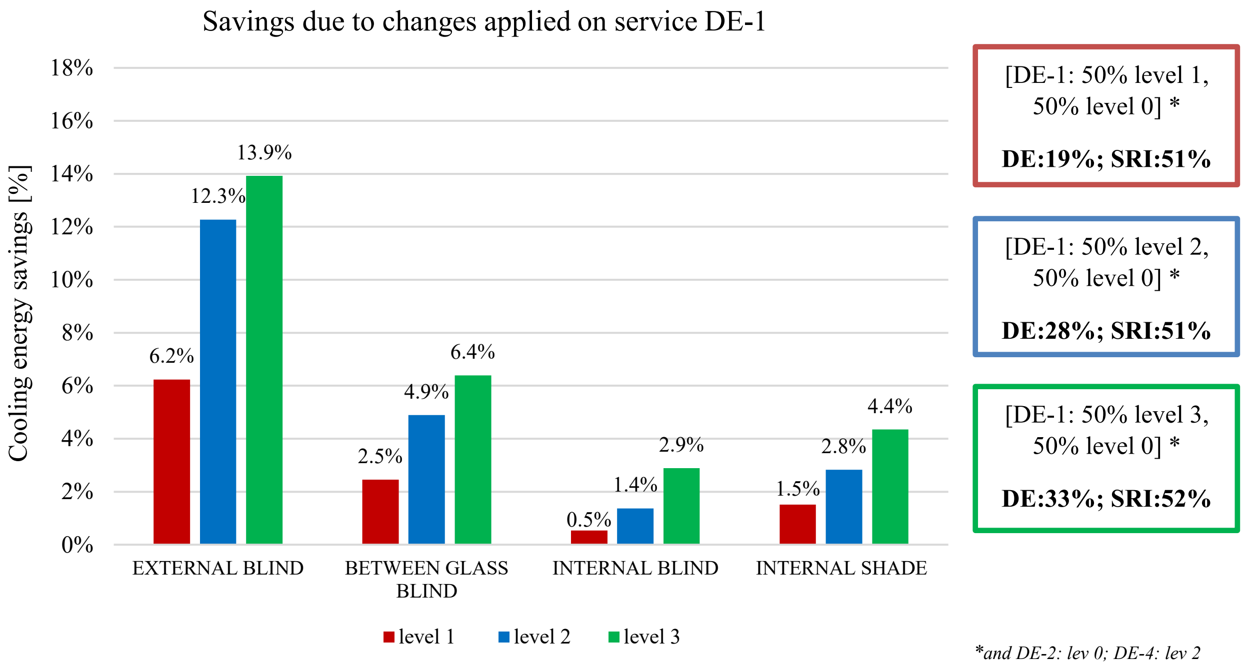


*Figure 83 - Cooling energy savings and SRI scores by upgrading the service DE-1*

*Table 20 - Cooling energy savings and SRI scores by upgrading the service DE-2*

| ***Application of DE-2, from level 0 to 2:*** | | | |
|---|---|---|---|
| | *functionality level 0 [kWh]* | *functionality level 2 [kWh]* | *savings [%]* |
| *Cooling energy needs* | 149’270 | 136’993 | 8.2% |

[DE-2: level 2] **

**DE:43%; SRI:52%**

** and DE-1: lev 0; DE-4: lev 2

By still a first view on the graph of fig.83, it appears evident that only three score assessments for the SRI correspond to twelve different values of cooling energy savings; no matter how much the cooling energy need is reduced, and so which kind of solar shading option is adopted, it becomes only a matter of how it is controlled. By focusing on a single solar shading type, the upgrade of the smartness level is correctly translated in an upgrade of the cooling energy savings and finally also a +1% on the final SRI comes from the assessment. On the other hand, by comparing the solar shading options, as expected, the performance of an external blind is much better than the one of an internal blind or internal shade, but for the SRI assessment if these different available solutions are controlled in the same way they have exactly the same impact on the SRI scores and the DE sub-score. This is a discussion already faced in the last Interim Report released on February 2020, talking about the "design passive features", with a member of a Topical Group arguing that, from an energy efficiency perspective, passive measures are preferred. He stressed that designers should be oriented towards passive measures by building codes or other regulations implementing the EPBD, before moving towards active measures [39]. The outcomes of the test done on EnergyPlus simulations are in line with these considerations. The study team tried to answer to the member group, believing that a distinction should be made between (i) the passive design features itself and (ii) the – potential – dynamic management capability of such a feature; in the first case, there is no reference to any dynamic management capability and so this implies no connection with the SRI assessment, being relative to something covered by the EPC, for instance, and this remark also illustrates the need to align the SRI to other schemes and certifications. "The second element relates to the dynamic management capabilities of passive features, e.g. automated control of solar shading devices. Although solar shading can be seen as a passive measure, the controls of solar shading can have different levels of smartness. Therefore, dynamic control of passive measures does fit within the scope of the SRI and is already represented in the service catalogue." Starting from this interpretation given about this issue, it is of course clear that the evaluation is about the degree of smartness, but the fact that I evaluated the degree of smartness of solutions – in this case window solar shadings – which have different energy performance cannot be considered out of relevance, if a smarter option of course should gain higher efficiency. Having clear that the SRI was introduced with the Energy Performance of Building Directive, here it seems that there is no communication through the Indicator that a building has a better performance using a certain control with a certain solar shading solution, stopping only to inform about the "certain control" adopted. In addition to this, also it is interesting to note how using for instance external blinds with a strategy control of level 1 is more efficient in terms of savings than using internal blinds with a higher functionality level. From another point of view, if I discuss about how to improve the energy performance of a building I'm discussing at the same time of how improving its smartness, but after these considerations on the results obtained with the simulations it seems that it is not immediate talking about a more efficient system when talking about a smarter solution. Moreover, "energy savings on site" is one of the impact criteria considered of relevance for the Indicator assessment.

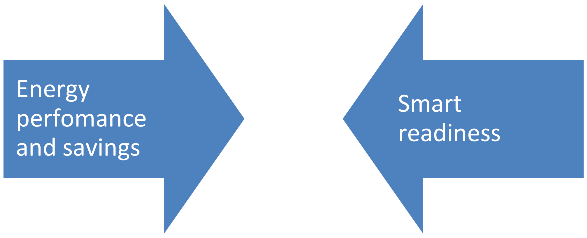


*Figure 84 - In which a direction a complete and better-defined SRI should go*

There is the need to a better-defined indicator leading to a more complete description and certification of the built environment in the framework of the energy transition and the smart building revolution, otherwise the SRI could become only a plus on the information of EPC, lost its value if considered alone. On the other hand, it must be stressed how the smart readiness is not the objective but the instrument thanks to which the energy efficiency, comfort and flexibility of building can increase.

Another comment on the results comes from the discussion about what happens if we consider the Dynamic Envelope or not, so the question rises in the chapter 3 can be deepened now, having also the results from the upgrades of both service DE-1, assigning the level 3 to the 50% and the 0 to the remaining 50%, and service DE-2 with its functionality level 2. The DE-4 is leaving at level 2.

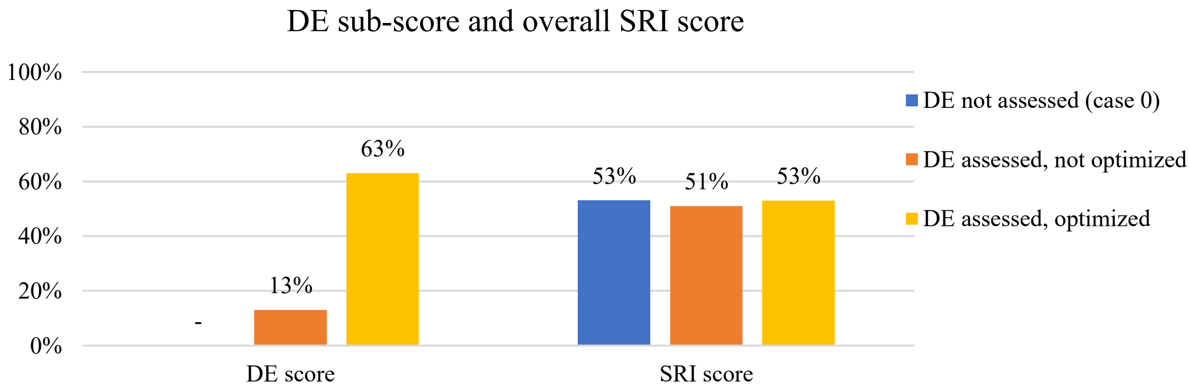


*Figure 85 - What happens to the scores, from the case 0 to the optimized one*

In the figure above, the case reported in blue refers to the basic model simulation involving 45 services, while for the other two cases 48 services are evaluated. So already from this first point of view of the comparison, the 53% has a different weight if the number of assessed services is reported with the overall score. In terms of cooling energy savings, with respect to the starting model with no solar shadings neither controls on the opening and closing of windows, there is a reduction of needs that, as explained in the graph above, would never be read on the overall

SRI score only, having the same 53% both in case 0 and in case of optimized Dynamic Envelope.

*Table 21 - Table to underline the savings obtained in the last simulated model*

| | *"district cooling" [kWh/y]* |
|---|---|
| *DE considered, not optimized* | 149’270 |
| *DE considered, optimized* | 117’117 |
| | |
| *saving in kWh* | 32’153 |
| *% of savings* | 21.5% |

As declared by the last graph, the issue of “be relevant or not” assumes a certain value in terms of overall score; it is clear that if no features involving the DE are present there is no possibility to assess functionality levels different from the 0 one, the non-smart functionality. On the hand, if something is not present, there is the need to better define “how thin is line” between “not relevant” and “not present”. This problem was faced before, also by mentioning other experts conducting the SRI assessment with other case studies, underlining the importance to define in a clear way the right choice for domains and relevant services. It appears that it is better to not consider the DE in spite of having very low functionality levels assessed for its services, of course. But, according to this, there is the need to understand in which way the Smart Readiness Indicator pushes for the implementation of new smart instruments and for the recognition of what is present as smart, even if not in a big amount. At this point, for instance the desirable distinction among buildings according to the year of construction or the renovation level could be a great distinction, considering for instance that for the Energy Center the presence of a dynamic envelope would be required and so assessed in each case.

There are open questions, but a clear evidence is that the higher the number of services analysed, the higher the “quality” of the percentage expressed by the overall score, but also it becomes higher the possibility to have a reduction in score. Of course, there is the need to give an overall percentage but being aware that without the number of services assessed over the total services it can be a not clear and complete information.

Another comment is about the sensibility of the sub-scores of the impact criteria, when passing from the DE not assessed to the DE improved:

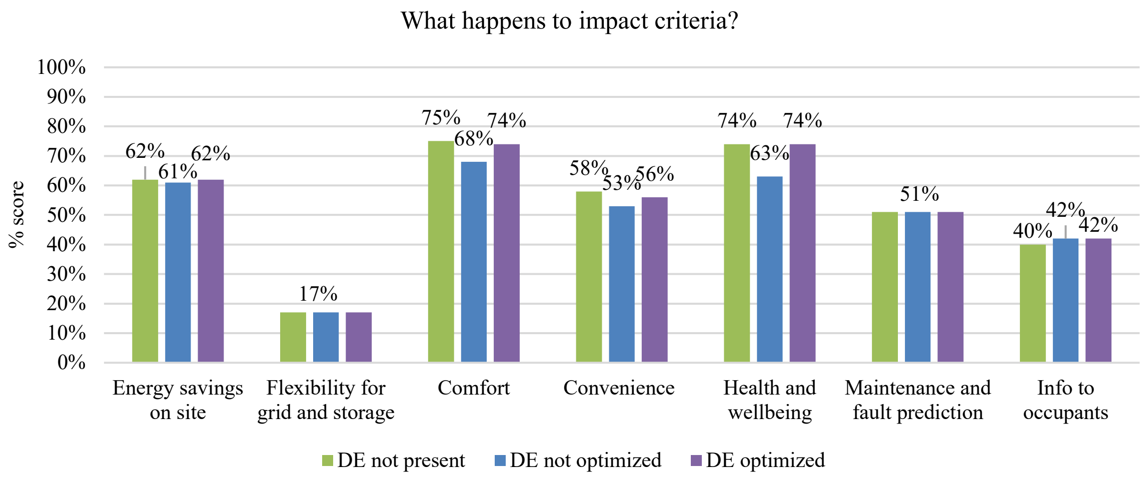


*Figure 86 - The Dynamic Envelope assessment affecting the impact criteria*

Here, there is again a comment related to the question about the relevance of a domain and if a not relevant domain has to be considered in each case in the assessment; I want in fact to underline that not having a solar shading and also, not having a solar shading control, would influence a lot the comfort or health and well-being side and it is not so realistic obtained a 1% less for comfort and the same percentage for health and well-being passing from "DE not present" to "DE optimize" case. These are merely opinions but, if there is the idea to discuss again on the issues about the relevance of the services, this could be a strong driving force to express the need in some cases to link the absence of something to a decrease in score.

It is evident that there are some open questions about the effectiveness of the SRI and its applicability, but it is also the moment – through analysis like these and the possibility to exploit instruments like the dynamic simulation tools – to discuss about this kind of issues and, supported by data and other tools, to find the optimized way to assess an indicator for smart readiness pushing towards the smart building revolution and supporting it at the same time.

# Conclusions

***Among metrics, indicators, real data and simulation models. The full correct approach to the whole building-occupants-plants-grids system***

In the energy transition framework towards the decarbonization process and a more interconnected, digitalized and sustainable world, there is a strong need of multi-disciplinary decision-making support tools supporting the challenges of this century.

Concerning the energy building sector, it is clearly time to go through this evolution. The Smart Readiness Indicator – if correctly introduced and assessed – could be the right instrument to support and encourage this challenging vision. However, in that "correctly introduced and assessed" there are still some issues to be solved, and in this work, I tried to analyse some of them. The discussion concerning the SRI is not only a matter of smart readiness and technology; there is now clearly the need to better describe the buildings we live in, to exploit all the ways we have to assess and to improve their performances, and to make use of suitable tools able to present in a clearer and faster way if buildings, occupants and plants are working well together or if there is space for improvement. The Smart Readiness Indicator tries to do this, putting together the needs of the occupants, plants and grids, in line with the sustainable energy transition vision.

However, this is not an easy point. Even though the use of a multi-criteria assessment method allows to touch all the aspects involved in the analysis, there could be still the risk to leave something out of focus or to give importance to something in spite of something else. It is in this context that becomes essential to define if the SRI could be supported by other tools, for instance linked to the EPC, so practically declaring that alone it loses its effectiveness.

However, what is sure is the relevance of this Indicator in order to take care of something that other mandatory regulations do not require, so that its assessment can be of relevance already during the project phase. Of course, if its point of strength is taking care of something new, like the dynamic capacity of the building to adapt to the energy and occupants' needs, which are not usually tackled in the traditional building assessments and certifications (e.g. EPCs), this cannot become also its point of weakness; indeed, even though it is interesting to consider all the possible smart-ready services and available technologies and controls a building could exploit, it is important not to lose sight of the primary goals of energy efficiency and improvements in energy performance that buildings need to achieve. This is among the outcomes of the previous section, which allowed to highlight how simulation models can be, as expected, valid tools to be exploited in these cases to support building performances assessment.

This is the crucial point. Indeed, an well-defined indicator can represent a key instrument to express and communicate, through a simple score or set of values, the energy behaviour of building also to a non-expert audience; however, the indicator needs to be supported by other kind of tools, among which simulation models and/or real data, which, in the era of digitalization, are more and more available. In other words, indicators are very powerful instruments, considering the great amount of information – quantitative and qualitative – they can manage and put together, but it is through the exploitation of tools like a dynamic simulation software, also supported by real data, that the smart building revolution could proceed faster and could achieve better results in less time.

The thesis tried to answer to some questions regarding how to follow the requirements and objectives of the European Union for the built environment, figuring out how the proposed Smart Readiness Indicator can be a step towards the smart goals, but underlying at the same time the relevance of other existing tools, like the dynamic simulation modelling or the data-driven analysis, which combination could help to validate the obtained results and certificate what happens in a real building.

Now that new advanced instruments and technologies are spreading, the next level will be to understand how to manage them together in order to deploy a full approach for responding to the multi-layer energy transition challenges, regarding energy, buildings, environment, transport, and, of course, human being.

*“We must develop a comprehensive and globally shared view of how technology is affecting our lives and reshaping our economic, social, cultural, and human environments. There has never been a time of greater promise, or greater peril.”*

Klaus Schwab, *Founder and Executive Chairman*, World Economic Forum

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