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Critical analysis on future developments for the Smart Readiness Indicator focusing on the functionality "Respond to users need"

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Abstract

Nowadays, the use of building automation and control systems is currently growing faster through the European continent, aiming to improve the energy efficiency, the building performance monitoring and to better respond to occupants' needs.

In 2018, the revised Energy Performance of Building Directive EU 2018/844 (EPBD) has introduced and updated a set of concepts with the aim of reach the total decarbonization of the European building stock, together with the reduction of the greenhouse gas emission within the 2030, respecting a minimum thresholds fixed at $-40\,\%$ of the levels registered in 1990.

For the first time, an indicator for the evaluation of the smart readiness of buildings has been introduced at the EU level, for which the adoption is still voluntary from European member states. This index, the so-called Smart Readiness Indicator (SRI), gives the possibility to better understand how and to what extent the considered buildings in the entire building stock are ready to adopt new smart solutions to improve their performance, bringing them closer to the 2050 goal of nearly Zero Energy constructions. Moreover, always based on the EPBD requirements, the SRI should be able to cope with the occupants' needs, enhancing the communication, the convenience but especially the comfort, health and well-being levels.

This thesis work is focused on the possible development pathways of the Smart Readiness Indicator, looking at the aspects of the SRI that are mostly related with the users' needs and suggesting improvements in the index's methodological framework proposed by the European Commission. A careful in-depth study concerning the Indoor Environmental Quality (IEQ) is carried out to provide modification in the SRI methodology, especially for the part related to the key capability "Respond to User's needs". The main focus concerns the way in which scores are evaluated and then assigned to each domain's level of functionality, and afterwards, the derivation of new weighting factors at the domains and impact criteria levels, used to compute the final SRI score. The revised scoring methodology is based on the calculation of Key Performance Indicators (KPIs) to assess comfort and health aspects, giving a score based on the performance level reached. Furthermore, the derivation of new weighting factors is based on the use of the Analytic Hierarchy Process (AHP), a Multi-criteria Decision Making method (MCDM), able to evaluate priorities over a set of proposed alternatives and criteria.

The intent of the entire work is to propose improvements in the actual methodology for the Smart Readiness Indicator to enhance the contribution and the importance of aspects related to the comfort and well-being in interior spaces.

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I am deeply grateful to all my family, especially my father, my mother, my sister and my little, fluffy dog Tea, that have always been standing by me in my life decisions and university career, pushing me to always do my best and to achieve great results.

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Per aspera sic itur ad astra.
Popular ancient motto.

1. Introduction

In modern times, the topic of energy efficiency has reached higher level of importance in the debate regarding the climate change and the possible development scenario that governments can adopt. A large amount of buildings in the European housing stock, approximating up to 90 % of the total, is made up of buildings with low energy-efficiency levels, for which the characteristics does not respond to the short-, mid- and long-term target imposed by the European Union. Indeed, a great part of buildings, that can still be used in 2050, are characterized by poor energy performance together with a lack in indoor environment conditions that are not able to guarantee adequate well-being conditions for occupants[22].

Usually, this two aspects are strictly related one to each other, insofar as a low performance of the building envelope can lead not only to higher energy consumption but also to micro-climatic conditions of interior spaces that can worsen the comfort conditions and the users' health and well-being. This condition can result in a phenomenon called the "Sick Building Syndrome", in which people show non-specific symptoms like headaches, fatigue or rash, that can negatively affect their life and productivity at work[54].

In this direction, the Energy Performance of Building Directive (EPBD) introduced for the first time in 2018 the Smart Readiness Indicator (SRI), a common European rating scheme that concerns the evaluation of the smart readiness of a building or a building unit. The assessment procedure is essentially based on the evaluation of capabilities that enable the building or the building unit to adapt itself and its overall performance to the users' needs and the energy grid, improving indoor environment conditions in a energy-efficient way[40].

1.1. Thesis structure

This Thesis work consist of eight chapters on future developments for the Smart Readiness indicator methodology, with a particular focus on the key capability related to "respond to users' needs". However, it can essentially considered composed by three main parts: a general overview to give more information about the arguments treated in effective research work, the section related to the research work carried out and finally a case study with the overall conclusions.

Starting from the most general, Chapter 2 starts by providing a reference Standard framework useful as an initial point of departure directly linked to what stated at the European level. The EPBD, together with EN 15232-1:2017 and ISO 52120-1:2022, are presented to introduce the concepts of energy efficiency, smart technologies and building automation, all related with the development of the SRI for the evaluation of the European building stock.

Afterwards, Chapter 3 describes Multi-Criteria Decision-Making (MCDM) methods with a specific focus on the Analytic Hierarchy Process (AHP) developed by T. L. Saaty[63] in order to compute a set of priorities across a set of alternatives and criteria. It involves directly decision-makers that through the use of questionnaires are able to express their opinion. The priorities are then provided using a mathematical procedure involving matrices and the computation of the principal eigenvector, used to derive the aforementioned weighting factors among alternatives and criteria.

In Chapter 4 is carried out a literature review on the Indoor Environmental Quality (IEQ) and Key Performance Indicators (KPIs). The IEQ is composed by Thermal comfort, Visual comfort, Indoor Air Quality (IAQ) and Acoustic comfort. For each of these categories a set of KPIs are presented, divided into steady-state key performance indicators and long-term ones.

For the conclusion of the first part, in Chapter 5 is reviewed and in-depth studied the Smart Readiness Indicator methodology developed by the European Commission. Firstly, the structure of the index is presented in order to better understand the different levels at which the SRI is developed and finally, a focus is made on particular features concerning the derivation of weighting factors and the computation procedure used to obtain the final SRI score.

The second part starts with Chapter 6, in which the thesis work is presented and developed only for the part concerning the SRI's key functionality "Respond to users' need". At first is proposed a new scoring methodology for assessing the level of a set of smart ready services that can be adopted in a building or a building unit. This new proposal is developed relying on the computation of the KPIs presented in Chapter 4 and scored used ranges given from regulations and literature review. Afterwards, the weighting factors actually used for the Smart Readiness Indicator are revised using the Analytic Hierarchy Process. For this purpose, a survey is prepared and proposed to a group of architects, engineer and experts in this field. The results are processed to obtain the new weightings for the methodology and to better reflect the real importance of criteria and domains for specific climate conditions and types of space.

In Chapter 7 in presented a case study in order to demonstrate what developed in the previous part. Finally conclusions about the entire thesis work are given in Chapter 8.

2. Reference Standard framework

Approximately 75 % of the existing constructions within the European Building Stock is considered to be energy inefficient and around to 75 % and 80 % is expected that will still be in use in 2050[32]. Until recently, the annual renovation rates has reached very low levels, around $0.4 - 1.2\,\%$, characterized by shallow retrofit actions, and buildings are considered responsible to consume up to 40 % of the European Union's final energy.

This situation is in stark contrast with the goals and the commitments that the involved States have endorsed in the document called Paris Agreement. Such document is a legally binding international treaty on climate change, developed during the Conference of Parties (COP) 21 on 12 December 2015 in Paris, and has become a reference point for what concerns the climate change process due to the fact that, for the first time it was a binding agreement that involves nations with the aim to cope with climate change, finding also strategies to adapt to its effects[39].

Consequently, at the European level a set of solutions, new policies, schemes and indicators has been introduced within a Standard framework, in order to accelerate the ecological transition, to improve energy efficiency, to reduce the total greenhouse gas emission an improve the comfort, health and well-being condition for users.

In the following sections are presented the main Standards considered in this thesis work and useful to its development.

2.1. The Energy Performance Building Directive (EU) 2018/844

Buildings are considered responsible for up to 36 % of the greenhouse gas emission at the European level[40]. Therefore, aiming to achieve the 2050 goal about the CO_2 neutrality of the European building stock, in 2018 the Energy Performance of Building Directive (EPBD) has been revised in order to establish a common direction for the improvement of energy efficiency and the achievement of a sustainable, competitive, secure and total decarbonized energy system[73], replacing the previous Directive version 2010/31/EU. Such Directive aims to enhance improvements in energy performance of new and existing buildings considering aspects related to outdoor climatic and local conditions, together with indoor environment requirements and cost-effectiveness[46].

This regulation scheme moves the attention on three main points regarding the enhancement of new strategies for energy efficiency improvement in new and existing constructions, the introduction of infrastructure related to e-mobility and the current increase in use of electric vehicles, and finally the implementation of performance monitoring through the use of smart building solutions.

For this purpose, each Member State undertakes to design a roadmap focused on renovation of its country building stock, including energy-efficient and cost-effective measures for both residential and non-residential construction. This long-term strategy shall provide an overview of the building stock situation, stimulating to deep-renovation actions and adoption of new solutions thanks to the use of government incentives and policies, in order to reduce the greenhouse gas emission up to $80-95\,\%$ compared to 1990 within 2050 and to transform the actual real estate into a nearly zero-energy buildings (nZEB)[40].

Moreover, the European Directive states that the improvement of energy efficiency should not only focused on the building envelope, but has strongly recommended the adoption of technical systems able to reduce the energy needs for heating or cooling, lighting and ventilation. Consequently, the EPBD states the importance in the adoption of Building Automation and Control Systems (BACS) with a view to reduce the amount of physical inspections and the introduction of Smart Ready Technologies (SRT) together with the digitization of the building industry, in order to improve comfort levels, to provide new services and infrastructures like e-mobility, and led to significant energy savings in a cost-effective way[40]. As showed in Fig.2.1, the expected advantages in use smart technologies can be summarized in four main points: the optimised energy use according to the local production, the optimised onsite energy storage, the automatic diagnosis and maintenance prediction and finally the improvement of interior comfort and well-being conditions for users.

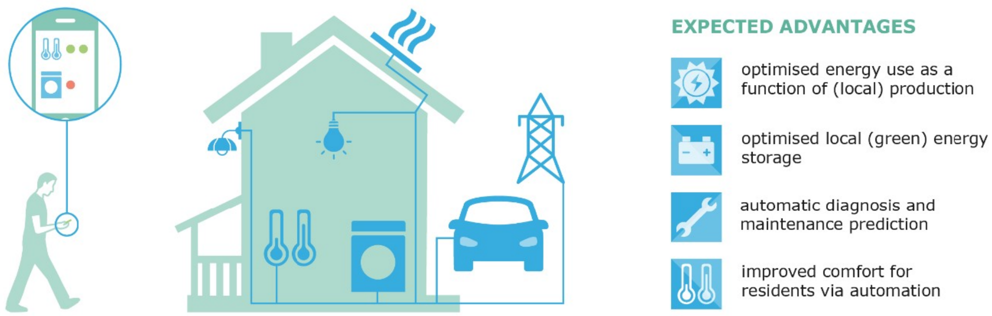


Figure 2.1: The expected advantages in adoption of Smart Technologies in buildings. Image from[31].

Therefore, the EPBD decides to introduces, in Article 8, a voluntary rating scheme in order to assess the level of "smart readiness" of buildings: the Smart Readiness Indicator (SRI). This index should be able to use Information and Communication Technologies (ICTs) together with electronic systems to adapt the building operation phase to the needs of occupants and the energy grid, improving the whole performance of constructions in the building stock. The methodology developed by the European Union for the Smart Readiness Indicator is drafted with the intent to use the most appropriate format for SRI, in order to make it simple, transparent and easily understandable for consumers, owners, investors and demand-response market[40]. The SRI score is determined through the assessment procedure of smart-ready services that are present or planned in the building or building unit, according to their functionality level, and it is expressed as a percentage of the total maximum score achievable.

Thus, the Smart Readiness indicator aims to make more tangible for people the added value related to the smartness of a building, encouraging consumers to invest in smart building technologies, linking its own methodology to other European schemes for rating energy efficiency, and supporting the rising technological innovation within the building sector[32].

2.2. The EN 15232:2017 and the new ISO 52120:2022

With the aim to support the Energy Performance of Building Directive (EPBD), the *Comité Européen de Normalisation* (CEN), named also European Committee for Standardization, has been involved in a standardization project sponsored by the European Union, developing a set of Standards focused on energy performance and the related minimum requirements. The EN 15232:2017 was included in this EU project, defining the methods to evaluate the impact of different degrees of functionality and complexity of Building Automation and Control System (BACS) and Technical Building Management (TBM) on the energy performance of buildings[74].

Recently, the EN 15232:2017 has been withdrawn and then superseded in March 2022 by the new EN ISO 52120-1:2022[70].

The term Building Automation and Control Systems, also referred to as Building Management System (BMS) is intended as the brain of the building[74], which integrates the information for all the technologies used in the built environment. In ISO 52120-1:2022 they are defined as "a system comprising all products, software and engineering services that can support energy-efficient, economical and safe operation of technical building systems through automatic controls and by facilitating the manual management of those technical building systems"[70].

It can be compared to a "platform" able to allow control, optimization and continuous monitoring of systems operation[30]. The BACS adoption is growing in recent times bringing ever closer to the EPBD objective of energy consumption reduction and adoption of BACS within 2025 in non-residential buildings (existing and new) with effective rated output of over 290 kW, where technically and economically feasible[40][36].

As stated by EN 15232:2017, the new ISO 52120:2022 specifies a structured list of controls with different building automation and technical building management functions ranging in degree of complexity (Fig.2.2) together with the associated method for the definition of minimum requirements. These data are organized in tables in which the first column specifies the number of the BACS and TBM function, the second column contains the field of application and the corresponding numbers of possible processing functions and finally the third refers to the specific processing functions providing the detailed commentaries.

5	Lighting control		
5.1	Occupancy control	LIGHT_OCC_CTRL	M9–5
	0	Manual on/off switch: the luminaire is switched on and off with a manual switch in the room.	
	1	Manual on/off switch plus additional sweeping extinction signal: the luminaire is switched on and off with a manual switch in the room. In addition, an automatic signal automatically switches off the luminaire at least once a day, typically in the evening to avoid needless operation during the night.	
	2	Automatic detection Auto on/dimmed off: the control system switches the luminaire(s) automatically on whenever the illuminated area is occupied, and automatically switches them to a state with dimmed status after the last occupancy in the illuminated area. Auto on/auto off: the control system switches the luminaire(s) automatically on whenever the illuminated area is occupied, and automatically switches them entirely off.	
	3	Automatic detection Manual on/ partial auto on /dimmed off: the luminaire(s) can only be switched on by means of a manual switch or automatically by occupancy detection sensor located in (or very close to) the area illuminated by the luminaire(s), and, if not switched off manually, is/are automatically switched to a state with dimmed status after the last occupancy in the illuminated area. Manual on/ partial auto on /auto off: the luminaire(s) can only be switched on by means of a manual switch or automatically by occupancy detection sensor.	
5.2	Light level/daylight control (daylight harvesting)	LIGHT_LEVEL_CTRL	M9–5
	0	Manual central: luminaires are controlled centrally, there is no manual switch in the room/zone.	
	1	Manual: luminaires can be switched off with a manual switch in the room.	
	2	Automatic switching: the luminaires are automatically switched off when more than enough daylight is present to fully provide minimum illuminance required and switched on when there is not enough daylight.	
	3	Automatic dimming: the luminaires are dimmed down and finally fully switched off, e.g. when daylight is available or when scene based light level control is applied. The luminaires will be switched on again and dimmed up if the amount of daylight is decreasing or when scene based light level control is applied.	

Figure 2.2: Example of BAC and TBM functions related to the lighting system that have an impact on the energy performance of buildings. Image from[70].

Moreover, two different calculation methodologies for the assessment of the effect that such functions give to the building are provided with two levels of detail: the first one is the easiest method and it is based on the so-called "BAC factors", i.e. based on a given energy performance, either a consumption metered or a demand calculated which is correlated to a certain BAC efficiency classification of the building[70]; while the second is defined as the detailed method, normally used when detailed information about the building, the automation, control, management functions type and the HVAC system are available[70][74].

In this way, it is possible to quantify and understand the quality level of building automation and control systems, using the Standard[70] as a tool useful to define the energy efficiency of BACS. Moreover, the energy efficiency can be expressed relying on the standard energy efficiency classes A, B, C and D, in which A is the best level and D the worst one. As will be seen later in this thesis work, the structure developed in

EN 15232:2017, and then also adopted for the current EN ISO 52120-1:2022[70], strongly resembles the methodological framework chosen for the European voluntary rating scheme of the Smart Readiness Indicator. Indeed, the categories identified as "Domains" in the SRI perfectly match with the field of use identified in ISO 52120:2022 in the second column of the possible functions' table. Moreover, even the different functions and the related degree of automation are strongly similar with the services and levels of functionality used to compute the scores in the Smart Readiness Indicator.

3. The Analytic Hierarchy Process: literature review of a Multi-Criteria Decision Making Method

The terms Multi-Criteria Decision-Making (MCDM) method, also called Multi-Criteria Decision Analysis (MCDA), refers to mathematical models that help to take decisions or solve a problem in scenarios in which all the possible alternatives are evaluated upon multiple conflicting criteria[13].

The MCDM process is often used as support for decision-making, by helping to structure the problem and improving transparency, consistency and analytic rigor of decisions[14]. Moreover, it is structured following six main steps, that include i) the formulation of the problem, ii) the identification of the requirements, iii) the set goals, iv) the identification of various alternatives, v) the development of different criteria, and finally vi) the identification and application of the most suitable decision-making technique[17]. There are different types of MCDA method and each of them has its own definition of best alternative. Furthermore, it is not guaranteed that, even using the same input data, the methods give the same results. In the following sections, is analyzed in detail one of the MCDM techniques, the Analytic Hierarchy Process (AHP), giving information from the general to the specific, in order to introduce to the final work of this thesis project.

3.1. The methodological framework of the AHP method

One of the most popular MCDM method is the Analytic Hierarchy Process (AHP) which has been developed by Thomas L. Saaty in 1971. It is used to establish measures considering both the physical and social domains, in order to derive priority scales using the pair-wise comparisons[63]. The AHP helps to solve complex problems that deal with conflicting and subjective criteria[10], which means that is primary used in order to find solutions when different alternatives useful to achieve the objective are compared under different criteria[23]. The core part of this method is composed by the process of measurements, in which the decision maker gives priorities related to all the items involved in the same hierarchical level using a ratio scale.

3.1.1. Problem modelling: the top-down structure

The methodology used by the AHP to solve problems is strongly based on the construction of a hierarchic or network structure that, starting from the top to bottom, is able to summarize the relationship between the main focus, the criteria, the possible sub-criteria and finally the alternatives from which the choice shall be made[63].

This step is defined as the "decomposition principles"[63], where the problem is structured in different levels, from the more general and abstract focus to the more particular and concrete features that led to achieve the objective.

Therefore, as showed in Fig.3.1, all the elements of this top-down structure are grouped together following an homogeneity criterion.

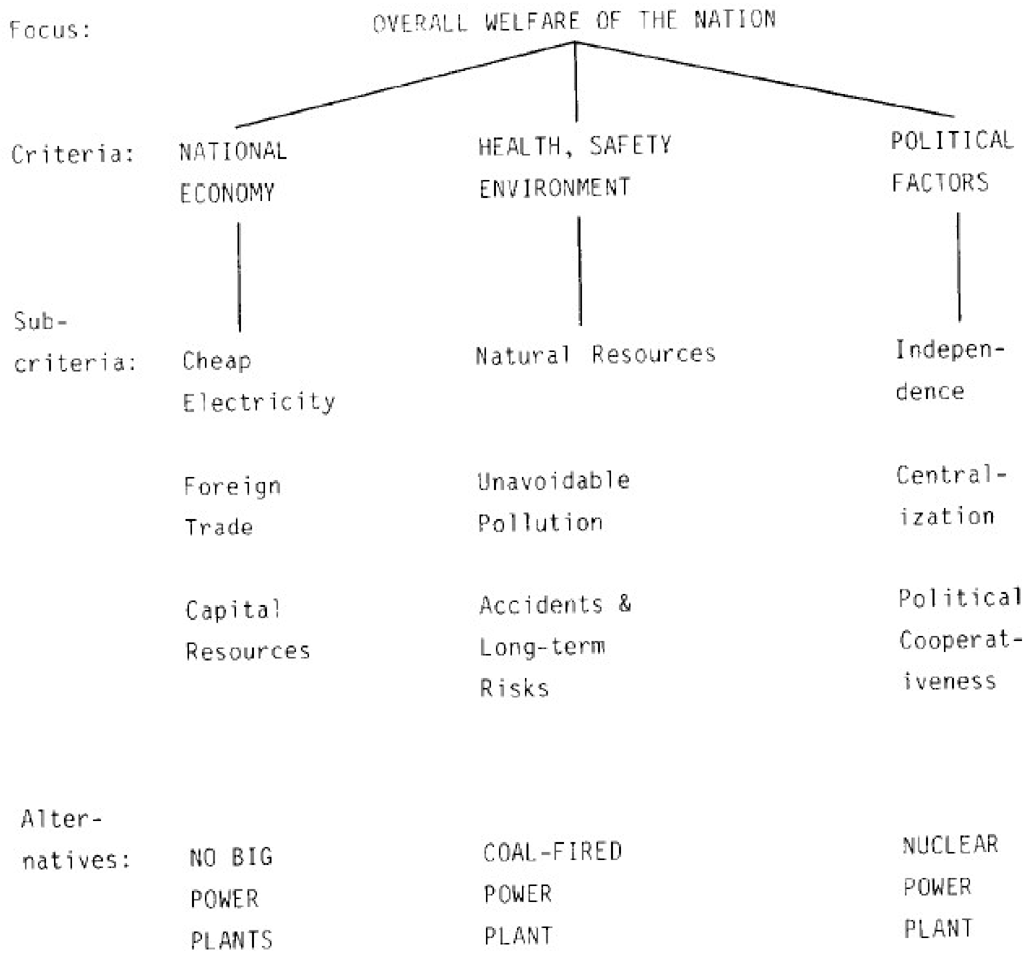


Figure 3.1: Example of a hierarchy (top-down structure) for the objective "Energy decision". Image from[63]

The top-down structure should be fairly detailed in order to capture the entire situation but flexible enough to be sensitive to changes[63]. This point is crucial, not only because it helps decision makers to better focus on specific criteria, but also because different structure may lead to a different final ranking[10].

3.1.2. The fundamental scale of the AHP

A judgment in the AHP method is made on a comparison between two elements belonging to the same level of the top-down structure or under the same criteria[64], with respect to the property that they have in common. From a mathematical point of view, a scale is defined as a "triple", thus composed by three main features: a set of numbers, a set of objects and a mapping of the objects to the numbers[64].

The Fundamental Scale of the AHP is an absolute scale, composed by positive real number from 1 to 9 that can express the degree of preference of an alternative with respect to another one, according to a specific criterion.

Therefore, the judgment is a relative value that express the importance of "element a" with respect to the "element b" that have the same unit[23]. Such judgment can also be expressed as a verbal appreciation, due to the fact that the fundamental scale provide the conversion from verbal statement to number[10]. Moreover, the possibility to express opinion using verbal responses is intuitively appealing, user-friendly and more common in everyday lives with respect to the use of numbers[10].

Intensity of importance	**Definition**
1	Equal importance
2	Weak or slight
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong or demonstrated importance
8	Very, very strong
9	Extreme importance
Reciprocals of above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i
Rationals	Ratios arising from the scale

Table 3.1: Fundamental scale of the Analytic Hierarchy Process (AHP). Data are from[64]

3.1.3. Surveys and construction of the comparison matrices

The main characteristic of this method is the construction of judgments matrices thanks to pairwise comparisons between criteria, sub-criteria or alternatives. The pairwise comparison approach is chosen according to the fact that it is easier and more accurate for people to express opinion on only two alternatives than simultaneously on all the alternatives. Due to this approach, the judgment matrices obtained from the AHP method are squared.

The step in which decision makers express priorities for the considered cluster, using the values included in the fundamental scale of the AHP, is defined as "comparative judgments" phase.

The minimum required number of judgments for a matrix of order n is equal to $n(n-1)/2$ because it is positive and reciprocal for definition, thus the diagonal elements are equal to 1 while the values in the lower matrix triangle are the reciprocals of the ones located in the upper matrix triangle.

The values in the matrix result from particular surveys that are carried out by people involved in the problem resolution. The question are normally structured comparing two elements and asking which has the property more, or which one satisfies the criterion more with respect to the other, i.e. which one is considered more important under a defined criterion and in which quantity, using the fundamental scale. A practical example of a typical question in surveys could be "How much more the criterion X is preferred over the criterion Y?. It is important to say that the way in which the comparison phrase is formulated can influence the judgments and consequently also the priority resulting from it.

3.1.4. Consistency of the data

When dealing with intangibles concepts, human judgment are necessarily inconsistent[65]. Indeed, the Analytic Hierarchy Process allows inconsistency because takes into account the fact that people are essentially inconsistent rather than consistent, so they are not able to evaluate accurately the measurement values, even if the judgment scale is well known.

In order to check the consistency of the data, it is important to check that the so-called "Consistency Ratio" (CR) is under a fixed threshold of 0.10. The first element that shall be computed is the Consistency Index (CI), which is strictly linked with the Eigenvalue Method (EM) used to derive priorities for criteria and alternatives. Indeed, its computation involves the use of the maximum positive eigenvector. Therefore, the CR is evaluated using the following equations:

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n-1} \tag{3.1}$$

where n is the dimension of the matrix and λ_{max} is the maximal eigenvalue of the matrix.

$$\mathrm{CR} = \frac{\mathrm{CI}}{RI} \tag{3.2}$$

where RI is the Random Index, i.e. the average Consistency Index of 500 randomly filled matrices. This value can be chosen from a table [Tab.3.2] resulting from Saaty's research work[10].

$\boldsymbol{n}$	3	4	5	6	7	8	9	10
$\boldsymbol{RI}$	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 3.2: Random Indices based on the dimension of the matrix. Data are from[63].

In the case of CR $>$ 0.10 the matrix shall be corrected. In practice, the judgments carried out by all the involved parties are not sufficient to bring the matrix to near consistency, due for instance to errors in the matrix construction and related to specific elements a_{ij} that shall be checked and substituted.

Therefore, such judgments should be detected analyzing the perturbation ϵ for each of the matrix element in order to identify which one is more affected by error. For this purpose, it is important to find the element a_{ij} of the matrix for which the perturbation ϵ is farthest from one[65]. In order to do that, a perturbation matrix is built and each element of such matrix is obtained multiplying the element a_{ij} of the starting judgment matrix by the ratio between the weight w_j and the weight w_i of the principal eigenvector of the starting matrix[65].

$$\epsilon_{ij} = a_{ij}\frac{w_j}{w_i} \tag{3.3}$$

The largest value obtained from this new matrix corresponds to the one that shall be changed for improve consistency of the data.

Afterwards, in order to determine the most consistent entry for the ϵ_{ij} element, as stated by Harker[49], the elements in the starting matrix at the position ϵ_{ii} and ϵ_{jj} shall be substituted with two while the elements at the position ϵ_{ij} and ϵ_{ji} shall be replaced with zeros. A new eigenvector w is computed for the latter matrix and the now-known value w_j/w_i and w_i/w_j of such eigenvector are substituted to the zeros, respectively in the positions a_{ji} and a_{ij}[65]. The two in the positions ϵ_{ij} and ϵ_{ii} return to be the starting values of the original judgment matrix.

At this points, the consistency ratio in checked once again. If the CR is lower than 0.10 the matrix is considered near consistent, on the other hand this procedure shall be repeated to fix the values responsible to matrix's inconsistency.

3.1.5. Determination of local and global weightings

The determination of the priorities in the Analytic Hierarchy Process is based on the Maximum Eigenvalue Method (EM)[23]. This is the final step of the methodology developed by Saaty[11].

In order to find the weighting factor for the involved alternatives and criteria, the principal eigenvector $w = (w_1, w_2, ..., w_n)$, i.e. the eigenvector associated with the largest eigenvalue λ_{max}, should be computed for each of the matrices obtained from the pair-wise comparisons at the different levels of the top-down structure. Therefore, all the element of each eigenvector shall be normalized by dividing each element w_i for the sum of all the w_i of the considered vector[63]:

$$w_i^n = \frac{w_i}{\sum_i w_i}$$

There are two types of local weights: the ones that represent how criteria affect each alternative and the ones that represent relative importance between the chosen criteria. All the first type vectors are joined together in order to form a new matrix that contains all the weighting factors related to the alternatives, that are multiplied by the criteria's eigenvector[63]. Finally, the resultant vector contains the global weights for the alternatives, for which the consistency ratio is checked with the sum of weighted inconsistency indices to the corresponding sums of weighted random indices[63].

4. Indoor Environmental Quality

4.1. What is Indoor Environmental Quality?

The indoor environment is a complex system made up of many different factors. The way in which it is modeled and its features are extremely important aspects that can affect people's health and well-being. This is due to the fact that, normally, people spent up to 90 % of time in indoor spaces[38], so indoor quality shall be considered when design interiors.

ASHRAE TC 1.6[33] has defined the Indoor Environmental Quality as the "perceived indoor experience about the building indoor environment that includes aspects of design, analysis, and operation of energy efficient, healthy, and comfortable buildings.". Thus, the indoor environmental quality (IEQ) can be expressed as the relative measure of comfort and healthiness perceived by the occupants that are exposed to indoor conditions[25].

Nowadays, across Europe and the entire world, a lot of certification for building start developing and are used, focusing not only on energy performance of the constructions, but especially on the level of comfort, well-being and health achieved by the interiors.

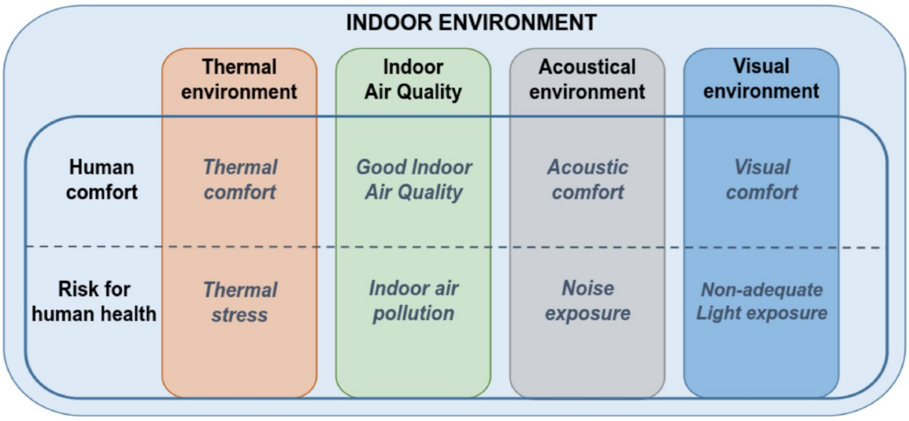


Figure 4.1: The four main aspects of the Indoor Environmental Quality (IEQ) and the related risks for human health and comfort. Image from[44]

With the term Health, the World Health Organization identifies not only the situation in which disease or infirmity are absent, but also the state of complete physical, mental and social well-being of the users[6]. Moreover, health risks for occupants are assessed looking at the exposure to potentially dangerous conditions, but including the evaluated primary containment measures and prevention activities. Consequently, risks related to the health of the occupants are generally evaluated using "pass/fail criteria"[44]. They are often quantitative tests that involve comparisons between the measured or calculated parameters in the indoor environment and the related limits threshold values, given by regulations or Standards.

On the other hand, the perceived level of comfort assessment can include quantitative, qualitative and subjective evaluation.

However, even if for the health assessment it is only necessary to meet the basic requirements, for what concerns the well-being sensation this is not sufficient, because it is fundamental to consider the comfort really perceived by the occupants.

These assessments are essential for the IEQ, term that shall include all the set of sub-components or sub-categories able to affect the human life, health and perceived level of comfort inside a building. These aspects, according to [28], can be identified with four main categories, that are the Thermal Comfort, the Indoor Air Quality (IAQ), the Visual comfort and the Acoustic comfort. In conclusion, the scheme showed in Fig.4.1 synthesized all the concepts up to now expressed about the IEQ.

In the following sections, the first three main aspects of the Indoor Environmental Quality (i.e. Thermal comfort, Indoor air quality and Visual comfort) are analyzed more in depth, also providing different comfort indices useful for the following parts of the thesis work. For what concerns acoustic comfort, it has been analyzed more in general due to the fact that it has not a primary role in the Smart Readiness Indicator methodology and in this work.

4.1.1. Thermal comfort

The definition of what is thermal comfort is given by the ASHRAE 55 which define it as the "condition of mind that expresses satisfaction with the thermal environment"[34]. The human body is a complex system which can be able to maintain its temperature constant through specific balancing actions with the surrounding environment. This behaviour consists in an equilibrium between the heat produced by the normal vital functions, i.e. transforming the chemical energy into heat (basal-metabolism), and the heat losses dispersed in the ambience[58]. Skin temperature is normally set around 37 °C, but in cold environment hands, feet, harms and legs can become colder than the body centre in order to protect the vital parts.

The ability to maintain constant the core-temperature, i.e. the internal temperature of the human body, is due to the presence of hypothalmus, a brain part that acts like a thermostat, together with many thermo-receptors located both in the brain's temperature centre and in the skin[58]. These thermo-receptors are divided depending on which type of stimulus are able to recognise: hot sensation or cold one. When thermo-receptors are stimulated, they transmit nerve impulses to the brain that cause the body reaction.

From literature review, there can be three different categories of factors able to influence the thermal comfort sensation[20] and are divided as follows:

- *Environmental factors*, that include the air temperature, the humidity, the air movement and the mean radiant temperature of the surrounding surfaces;

- *Personal factors*, which include the activity carried out by a person, also called metabolic-rate, and the clothing insulation level, so the ability of the clothing layer to minimize the heat exchange with the environment;
- *Contributing factors*, including the quantity of subcutaneous fat, the age, the gender or the state of health.

For the ASHRAE 55 this factors can be summarized in the six primary drivers that shall be considered when dealing with thermal comfort: i) metabolic rate, ii) clothing insulation, iii) air temperature, iv) radiant temperature, v)air speed and finally, vi) humidity. Such physiological and environmental factors combined with psychological ones, can differ between people making difficult to satisfy thermal comfort for every occupant in a space.

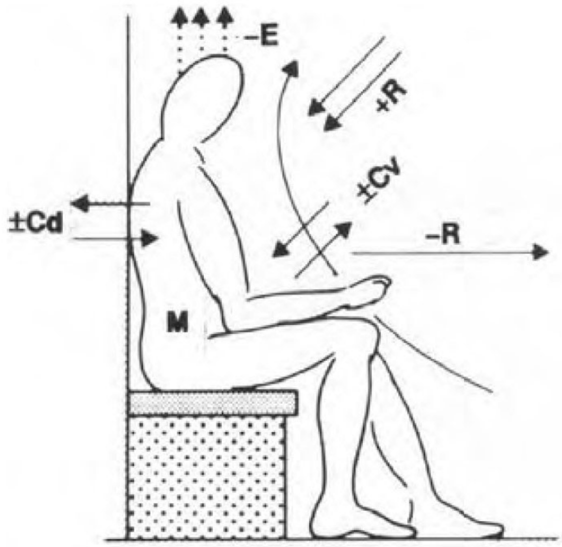


Figure 4.2: Heat exchange mechanisms of the human body. Image from [8]

The following parts report some indices normally used for the assessment of thermal comfort. They are resulting from International standards, regulations or literature review. These indices are organized following the differentiation between "steady-state", so indicators able to evaluate a required performance in a defined moment, and "long-term" ones, so capable of evaluating a performance after a defined time period.

Short-term indicators

Predicted Mean Vote (PMV)

The Predicted Mean Vote (PMV) is an index developed by Fanger in 1966 and used to assess the thermal comfort in indoor environments. It is based on the prediction of an average value regarding a large group of people in an indoor space, with a particular combination of air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate and clothing insulation[71].

This index is based on a seven-point thermal sensation scale (see Tab.4.1) that takes into account the heat balance of the human body.

Vote	**Thermal sensation**
+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
−1	Slightly Cool
−2	Cool
−3	Cold

Table 4.1: Seven-point thermal sensation scale. Data are from [71]

The reference standard framework includes ASHRAE 55[34], ISO 7730:2005[71] and EN 16798-1:2019[68]. This method is based on the correlation between the subjective human perception and the difference between the heat generated and the heat released by the human body.

From ISO 7730:2005[71] the PMV is computed as follows:

$$\begin{aligned}\text{PMV} =&[0.303 \cdot \exp(-0.036 \cdot M) + 0.028]\cdot \\ &\{(M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - p_a] - 0.42 \cdot [(M - W)- \\ &58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a)- \\ &3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} \cdot h_c\}\end{aligned} \tag{4.1}$$

$$\begin{aligned}t_{cl} = 35.7 - 0.028 \cdot (M - W) - I_{cl} \cdot \{3.96 \cdot 10^{-8}\cdot \\ f_{cl} \cdot [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} \cdot h_c\}\end{aligned} \tag{4.2}$$

$$h_c = \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} & \text{for} 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \\ 2.38 \cdot |t_{cl} - t_a|^{0.25} & \text{for} 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1 \cdot \sqrt{v_{ar}} \end{cases} \tag{4.3}$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 l_{cl} & \text{for} l_{cl} \leq 0.078 m^2 \cdot K/W \\ 1.00 + 1.290 l_{cl} & \text{for} l_{cl} < 0.078 m^2 \cdot K/W \end{cases} \tag{4.4}$$

where M is the metabolic rate (W/m^2), W is the effective mechanical power (W/m^2), I_{cl} is the clothing insulation (m^2·K/W), f_{cl} is the clothing surface area factor, t_a is the air temperature (°C), t_r is the mean radiant temperature (°C), v_{ar} is the relative air velocity (m/s), p_a is the vapour partial pressure (Pa), h_c is the convective heat transfer coefficient (W/m^{2}K) and t_{cl} is the clothing surface temperature (°C).

Equation 4.1 can be calculated using a computer program called BASIC and given by the ISO 7730:2005[71]. Another ways to compute this index could be using PMV tables from the aforementioned Standard, which taking into account different types and combination of activity, clothing, operative temperature and relative velocity, or finally by direct measurements in the environments.

Predicted Percentage of Dissatisfied (PPD)

The Predicted Percentage of Dissatisfied (PPD) quantifies the expected percentage of dissatisfied people in a given thermal environment. Thus, it considers people that express a thermal sensation equal to hot, warm, cool or cold with respect to the seven-point scale showed in Table4.1. After the computation of the PMV, the PPD is given by the following equation:

$$\mathrm{PPD} = 100 - 95 \exp\left[-0.03353 \cdot \mathrm{PMV}^4 + 0.2179 \cdot \mathrm{PMV}^2\right] \tag{4.5}$$

Due to individual differences between people, even for the situation of thermal neutrality (PMV = 0), the percentage of dissatisfied is 5 %, as showed in Fig.4.3.

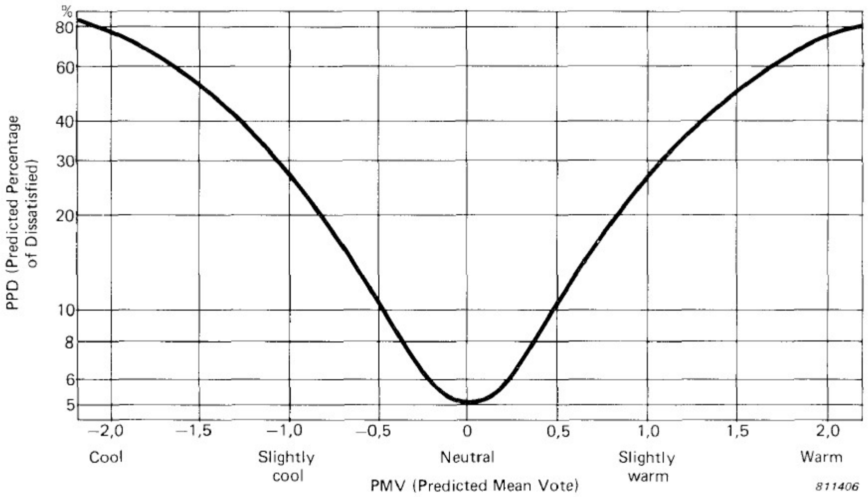


Figure 4.3: Relationship between Predicted Percentage of dissatisfied (PPD) and Predicted Mean Vote (PMV). Image from [58]

Local thermal discomfort

Local thermal discomfort phenomena can occur when a particular part of the body is overheated or overcooled. This is due to the fact that, mostly at people who carried out sedentary activity, the PMV and PPD indices assess an overall situation of thermal comfort for the entire body, which is very close to neutrality. Consequently, localized changes in air speed or surface temperature can cause discomfort situations for the occupants and a specific part of their body. Local thermal discomfort indices that shall be considered are:

- *Draught ans air speed.* The first one is evaluated with the percentage of people that experiment discomfort due to localized air flows at the neck. From ISO 7730:2005[71] draught phenomenon is computed as follows:

$$DR = (34 - t_{a,I})(v_{a,I} - 0.005)^{0.62}(0.37 \cdot v_{a,I} \cdot Tu + 3.14) \tag{4.6}$$

$$\begin{cases} \text{for } v_{a,I} < 0.05m/s & \text{use } v_{a,I} = 0.05m/s \\ \text{for } DR > 100\% & \text{use } DR = 100\% \end{cases} \tag{4.7}$$

where $t_{a,I}$ is the local air temperature (°C), which ranges from 20 °C to 26 °C; $v_{a,I}$ is the local mean air velocity (m/s), normally less than 0.5 m/s; Tu is the local turbulence intensity, measured in percentage and normally with values ranging from 10 % to 60 % (for unknown value Tu=40 %). For the air speed, the standards ISO 7730:2005[71] and the EN 16798-1:2019[68] establish ranges for air speed related to the three comfort categories, from I class (the best) to the III class (less comfortable).

- *Vertical air temperature difference.* It is assessed using the Percentage of Dissatisfied (PD) as a function of vertical air temperature difference between head and ankles. In particular, people are more likely to experience discomfort when the temperature increases upwards than if it decreases. From ISO 7730:2005[71] the vertical air temperature difference is computed with the following equation:

$$\text{PD} = \frac{100}{1 + \exp(5.76 - 0.856 \cdot \Delta t_{a,v})} \tag{4.8}$$

where PD is the percentage of dissatisfied people while $\Delta t_{a,v}$ is the vertical air temperature difference between ankles and head (°C). This formula should only be used at $\Delta t_{a,v}$ < 8 °C. The relationship between PD and vertical air temperature difference is explained in Fig.4.4.

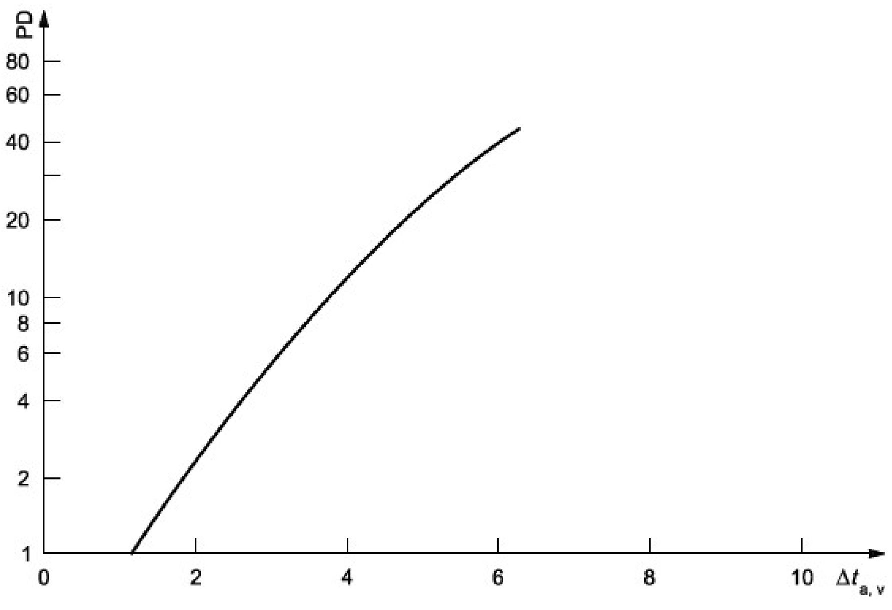


Figure 4.4: Local discomfort caused by vertical air temperature difference: relationship between Percentage of dissatisfied (PD) and vertical air temperature difference between head and feet($\Delta t_{a,v}$). Image from [71]

- *Warm and cool floor.* Too cool or too warm floor surfaces can caused uncomfortable sensation for the occupants. Consequently, ISO 7730 provides the assessment of this phenomenon using the Percentage of Dissatisfied (PD) as a function of the floor temperature. This index is computed as follows:

$$\text{PD} = 100 - 94 \exp\left[-1.387 + 0.118 \cdot t_f - 0.0025 \cdot t_f^2\right] \tag{4.9}$$

where t_f is the floor temperature (°C). The relationship between the PD and the floor temperature is showed in Fig.4.5.

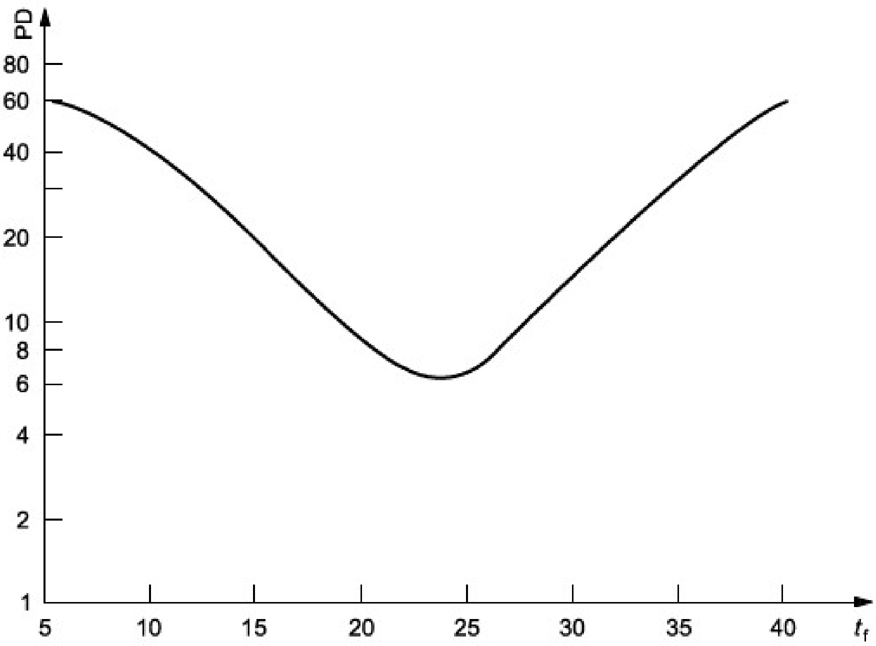


Figure 4.5: Local discomfort caused by warm or cool floors: relationship between Percentage of dissatisfied (PD) and floor temperature (t_f). Image from [71]

- *Radiant asymmetry.* People are more likely to experience discomfort from cool walls like windows or warm floors. As showed in Fig.4.6 the is index is computed with a Percentage of Dissatisfied (PD) as a function of the radiant temperature asymmetry caused by the too hot or too cold surfaces.

  The radiant temperature asymmetry is computed in the following methods depending on which type of surface is considered:

$$\begin{aligned} \text{PD}_{warmceiling} =& \frac{100}{1 + \exp(2.84 - 0.174 \cdot \Delta t_{pr})} - 5.5 \\ \text{with } \Delta t_{p,r} < 23\,^{\circ}\text{C} \end{aligned} \tag{4.10}$$

$$\begin{aligned} \text{PD}_{cool,wall} =& \frac{100}{1 + \exp(6.61 - 0.345 \cdot \Delta t_{pr})} \\ \text{with } \Delta t_{p,r} < 15\,^{\circ}\text{C} \end{aligned} \tag{4.11}$$

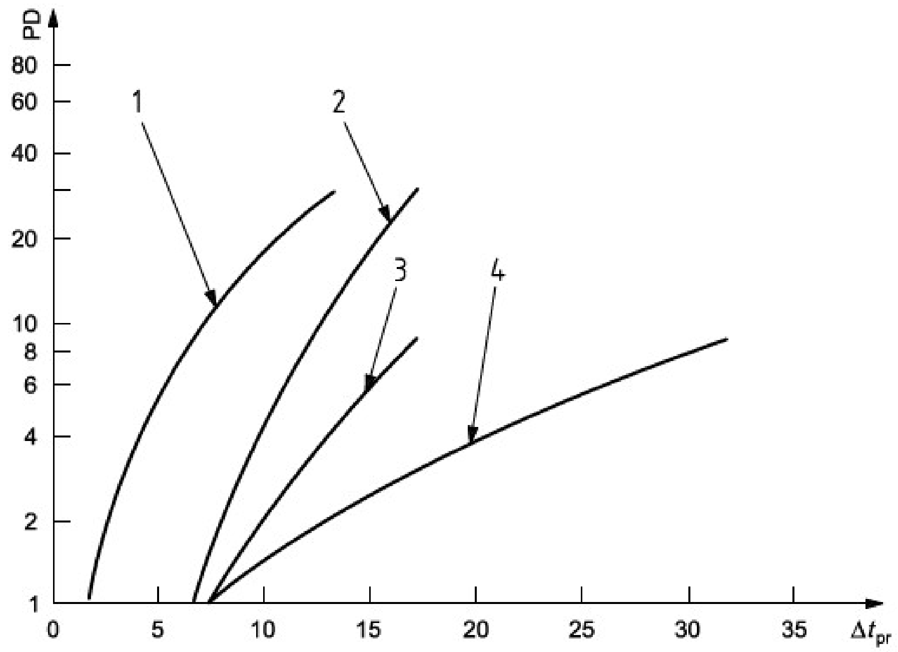


Figure 4.6: Local discomfort caused by radiant temperature asymmetry: relationship between Percentage of dissatisfied (PD) and radiant temperature of warm ceilings (1), cool walls (2), cool ceilings (3) and warm walls (4). Image from [71]

$$\begin{aligned} \mathrm{PD}_{cool,ceiling} =& \frac{100}{1+\exp(9.93-0.50\cdot\Delta t_{pr})} \\ \text{with}\, \Delta t_{p,r} <& \; 15\,^{\circ}\mathrm{C} \end{aligned} \tag{4.12}$$

$$\begin{aligned} \mathrm{PD}_{warm,wall} =& \frac{100}{1+\exp(3.72-0.052\cdot\Delta t_{pr})} - 3.5 \\ \text{with}\, \Delta t_{p,r} <& \; 35\,^{\circ}\mathrm{C} \end{aligned} \tag{4.13}$$

Long-term indicators

Percentage Outside Range (POR)

The Percentage Outside Range (POR) belongs to the category of percentage indices, that are assessed computing the amount of time in which a comfort threshold is exceeded with respect to the total number of occupied hours[62]. In particular, this index indicates the percentage of time outside the comfort PMV range or the operative temperature defined by regulation for a specific comfort category. The reference standard framework includes ISO 7730:2005[71] and EN 16798-1:2019[68]. The POR that used PMV ranges as reference is computed with the following equation:

$$\mathrm{POR}_{\mathrm{PMV}} = \frac{\sum_{i=1}^{Oh}(wf_i * h_i)}{\sum_{i=1}^{Oh} h_i} \in [0;1] \tag{4.14}$$

$$\begin{cases} wf_i = 1 \leftarrow (\text{PMV} < \text{PMV}_{lowerlimit} \vee (\text{PMV} > \text{PMV}_{upperlimit}) \\ wf_i = 0 \leftarrow (\text{PMV}_{lowerlimit} \leq \text{PMV} \leq \text{PMV}_{upperlimit}) \end{cases} \tag{4.15}$$

The same index computed using operative temperature instead of the PMV range is the following:

$$\text{POR}_{\Theta op} = \frac{\sum_{i=1}^{Oh}(wf_i * h_i)}{\sum_{i=1}^{Oh} h_i} \in [0;1] \tag{4.16}$$

$$\begin{cases} wf_i = 1 \leftarrow (\Theta_{op,actual\text{PMV}} < \Theta_{op,lower\text{PMV}limit} \vee (\Theta_{lower\text{PMV}limit} > \Theta_{upper\text{PMV}limit}) \\ wf_i = 0 \leftarrow (\Theta_{lower\text{PMV}limit} \leq \Theta_{op,actual\text{PMV}} \leq \Theta_{upper\text{PMV}}) \end{cases} \tag{4.17}$$

However, POR does not give information about the degree of severity in which a discomfort situation occurs, but can be a simple method to compare comfort performances in different situation or buildings[37].

Severity of Dis-compliance (SD)

The Severity of Dis-compliance (DS) is an index which corresponds to a daily average score for each of a pre-defined set of considered parameters able to explain the severity of a particular situation regarding comfort, health and well-being assessment[45]. The reference for this index came from a literature review[45] and it is based on international standards like EN 16798-1:2019 or ISO 7730:2005 for what concerns the comfort ranges considered for the computation.

This index is computed starting from sub-indicator called Severity of hour Outside Range (ShOR) that evaluates the severity of an indoor condition through the monitoring of chosen parameters referring to occupants' health and well-being. It can range from 0 (not severe) to 3 (very severe) based on which ISO 7730:2005 comfort category[71] it belongs. In particular, comfort class I is scored as 0, class II equals 1, class III equals 2, while an hour outside the comfort class III is scored 3. In addition, how reported in Ref.[45], this sub-indicator can be translated into graphical information in order to make clearer the comprehension of the results.

Class	Score	Colour code
I	0	
From I to II	1	
From II to III	2	
Over III	3	

Table 4.2: Comfort classes with related scores and associated colour code. Data are from[45].

The Severity of Dis-compliance is then computed as a daily average ShOR(x) per each of chosen parameter, using the following equation:

$$SD(x) = \frac{\sum_{i=1}^{Oh} ShOR(x)_i}{Oh}[0-3] \tag{4.18}$$

where $ShOR(x)_i$ is the score per hour reached by the parameter "x" while Oh are the occupied hours.

Afterwards, the effective indicator is computed as the weighted sum of the daily average scores assessed in terms of ShOR(x), as follows:

$$\mathrm{SD} = \sum_{i=1}^{n} \alpha_n SD(x)[0 - -3] \tag{4.19}$$

where α_n is the -n weight associated to each parameter "x". In the case of Ref.[45] all the parameter used are considered with the same weighting factor.

4.1.2. Indoor Air Quality

The Indoor Air Quality (IAQ) refers to the physical, chemical and biological characteristics of air in the enclosed environment and it has a significant impact on comfort perceived by the occupants and their health[18]. Considering that people spend long periods of time in indoor environments in addition to the increase of pollution levels also in indoor environments and its awareness, standards and regulations for the IAQ has been developed by political institutions, environmental governances and international scientific community for improving the comfort, health and occupants' well-being in several countries[9].

An important study, conducted by the United States Environmental Protection Agency (EPA) in 1998, has reported that indoor concentration of pollutants, together with indoor exposure, is respectively 1-5 times and 10-50 times higher than outdoor ones[4]. For ASHRAE, the indoor air quality is considered acceptable when “it does not contain known contaminants in harmful concentrations, as established by the competent authorities, and for which a substantial majority of people exposed (80 % or more) does not express dissatisfaction”[35].

In addition to outdoor pollutants, that can enter into the indoor spaces by infiltration, the indoor air contains a large amount of indoor contaminants that are produced from combustion sources (e.g. tobacco products or candles), biological activity of the human body, materials used for the construction, cleaning products, pets and also from humidification devices or heating/cooling systems[9]. Indeed, IAQ can be affected by particular matter, organic and inorganic gases, volatile organic compounds (VOCs) and biological particulate matter like fungi and bacteria. In the second edition of the WHO air quality guidelines (AQGs)[5], which was considered as a starting point for the EU Air Quality Directive and the definition of legally binding limit values, 35 air pollutants are concerned (see Table4.3).

Because of the IAQ can have impacts on occupants' productivity as well as on their health, a set of metrics has started to develop in order to evaluate the concentration of the main pollutants and the quality of indoor air. Normally, two groups of indices are used: the one that measures the concentration of one or more types of pollutants, and the group that includes guideline values such as CO_2 concentration and ventilation rate[18], used especially in the standards like EN 16798-1:2019[68].

Organic Pollutants	**Inorganic Pollutants**
Acrylonitrile; Butadiene; Benzene; Carbon disulfide; Carbon monoxide; 1.2-Dichloromethane; Dichloromethane; Formaldehyde; Polycyclic aromatic hydrocarbons; Polychlorinated biphenyls; Styrene; Tetrachloroethylene; Toluene; Trichloroethylene; Vinyl chloride; Polychlorinated dibenzodioxins and dibenzofurans.	*Arsenic; Asbestos; Cadmium; Chromium; Fluoride; Hydrogen sulfide; Lead; Manganese; Mercury; Nickel; Platinum; Vanadium.*
Classical Pollutants	**Indoor Air Pollutants**
Particulate matter; Ozone and other photochemical oxidants; Nitrogen dioxide; Sulfur dioxide.	*Man-made vitreous fibers; Environmental tobacco smoke; Radon.*

Table 4.3: Summary of the most important indoor air pollutants for the WHO air quality guidelines (AQGs). Data are from [5].

In the following paragraphs are describes two indicators provided by the reference standard framework and used to evaluate the indoor air quality in buildings.

Ventilation rates based on perceived IAQ

The standard EN 16798-1[68] gives three methods useful to design and assess the indoor air quality. Establishing ventilation rates in relation to how people perceive the IAQ conditions is one of them. The total ventilation rate q_{tot} (l/s) is expressed as the contribution of two important elements: the ventilation rate for occupancy per person, the so-called bio effluents, and the ventilation rate for the emissions related to the building.

Consequently, from EN 16798-1[68] the ventilation rates based on perceived IAQ are computed as follows:

$$q_{tot} = n \cdot q_p + A_R \cdot q_B \tag{4.20}$$

where q_{tot} is the total ventilation rate for the breathing zone (l/s), n is the design value for number of people in the room, q_p is the ventilation rate for occupancy per person (l/s person), A_R is the floor area (m^2) and q_B is the ventilation rate for emissions from building (l/(s·m^2)). With the terms "breathing zone", the EN 16798-1[68] refers to the part of the occupied zone at the head level of the occupants, which can range from 1.7 m for people standing to 1.1 m for seated people and finally to 0.2 m for children on the floor.

CO_2 concentration

Another way to assess indoor air quality (IAQ) is to evaluate that the concentration of particular pollutants in the air do not exceed the limit thresholds prescribed by the international standards or regulations. An example is the evaluation of CO_2 concentration, which is one of the main indoor pollutants due to the biological activity of the occupants. For this purpose, EN 16798-1[68] establishes limit thresholds related to the comfort category chosen for the building.

4.1.3. Visual comfort

Indoor environments shall be properly illuminated to ensure different visual performances. Different degrees of visibility and comfort depend on the type and the duration of the activity carried out by the occupants.

The reference standard framework includes at first Standard EN 17037:2018[69], that shows all the features of daylight in buildings, which should be a significant source of illumination thanks to the openings. Daylight provides high colour rendering and variability changing through the days and seasons, and can actively contribute to the psychological well-being of the occupants. On the other hand, the Standard EN 12464-1:2021[67] provides all the information regarding electric lighting requirements for workplaces in order to meet the needs for visual comfort and performance for people with normal (or corrected to normal)ophthalmic visual capacity.

Moreover, light can have visual and non-visual effects on the users: the first ones are related to how light can illuminate the interiors and how it can shape the environment, while the seconds are referred to the impact of light on the human circadian rhythms. Thus, the main criteria that shall be considered when dealing with electric lighting and daylight are the:

- luminance distribution, that is able to control the level of adaptation of the eyes and to affect the capacity to see. For this reason, standards[67][69] suggest to avoid too high luminances and luminance contrasts, high luminance variation and too low luminances and too low luminance contrasts that can cause a sense of fatigue for the occupants;

- illuminance, that can determine how quickly, safely and comfortably a person perceives and carries out a specific visual task. Thus, different values of illuminance are given based on the performance needs;

- glare, that corresponds to the unpleasant sensation produced by bright areas in the visual field or reflections of the light, and can be avoided by shielding the light source or limiting the luminance of surfaces;

- directionality of light, so the orientation of the light source that can help to fulfil the visual task but always considering the glare problem;

- colour rendering and colour appearance, respectively the apparent colour (i.e. chromaticity) of the light emitted, quantified using the correlated colour temperature, and the accuracy with which the colours are viewed;

- flicker and stroboscopic effect or so-called Temporal Light Artefacts (TLA), that are faults in light emission that can cause fatigue, headaches and also dangerous situation for human health;
- variability (levels and colour), so the possibility to vary the illuminance, the colour temperature or spectrum of light during the day or the seasons, in order to enhance users' well-being and productivity.

The following paragraphs report some indicators for the evaluation of visual comfort, resulting from International standards, regulations or literature review. They are organized following the differentiation between "short-term" indicators, so indices able to evaluate a required performance in a defined moment, and "long-term" indicators, capable of assessing a performance after a defined time period.

Short-term indicators

Illuminance

Illuminance is a short-term metric measured in *lux* that is able to assess the amount of light at a point P of a given reference surface, normally defined as "workplane". It is computed as the ratio between the luminous flux incident on the infinitesimal surface in the neighborough of P and the area of the surface[29]. A synthetic formula is given below:

$$E_{\mathrm{P}} = \frac{\mathrm{d}f}{\mathrm{d}A_{rec}} \tag{4.21}$$

Based on the type of visual task that needs to be performed, different threshold-value are defined in the standards EN 17037:2018[69] and EN 12464-1:2021[67]. Some important features that characterized this indicator are that the measure is local and strictly related to the position and the orientation of the surface, it does not consider variation over time but give an instantaneous evaluation, it can not evaluate the glare risk because it does not depend on the eye of the observer, and finally it does not consider the nature of the light source, so it can be used to assess both the amount of artificial or natural light.

Daylight Factor (DF)

The daylight Factor (DF) is a metric used in EN 17037:2018[69] to assess the amount of natural light in interior spaces at a given point of a reference surface. The *Commission International de l'Eclairage* (CIE), together with the aforementioned Standard, define the Daylight Factor as "the quotient of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution and the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded"[69][2]. It is computed using a standard CIE overcast sky, which is characterized by a sky luminance rotationally symmetrical about the vertical axis, with no sun[55]. Consequently, due to the symmetry of the chosen sky type, the DF does not depend on the orientation or location of the considered point in a space and it can be computed using the following equation:

$$\text{DF} = \frac{E_{in}}{E_{ext,hor}} \cdot 100 \tag{4.22}$$

where E_{int} is the interior illuminance at a point on a reference plane, while $E_{ext,hor}$ is the exterior horizontal illuminance for a standard CIE overcast sky. Moreover, the Daylight Factor is expressed in percentage and was developed around sixty years ago in the United Kingdom.

As reported by EN17037:2018, the Daylight Factor can be also used as a long-term metric, comparing it to a target daylight factor (D_t) that should be achieved for at least half of the daylight hours[69].

Equivalent Melanopic Lux (EML)

Non-visual effects of the light are essential for the human health in controlling the biological clock, sleep-wake routine and psychological aspects of people's life. All these biogical and behavioural aspects depend on distinct photo-receptors located behind the eyes, called melanopsin-containing intrinsically photosensitive retinal ganglion cells (ipRGCs)[1]. They are additional photo-receptors with respect to the well-known rods and cones useful to perform the visual task. The effects on the human body are directly correlated to the production of two foundamental hormones: the melatonin, responsible of the sleep and relax phase, and the cortisol, that regulates the alertness and psychomotor reaction time in a person. When light stimulates the eyes, pupils are contracting and suppress the melatonin production while increasing the cortisol one. An important aspect that shall be taken into account is that biological photo-receptors are not equally sensitive to light for all wavelengths. This means that rod opsin (i.e. the photopigment of rod photo-receptors) is much more sensible to a wavelength of 500 nm; the three types of cones -namely S, M and L- are maximally sensitive respectively to 420 nm, 535 nm and 565 nm, and finally the ipRGCs are more sensitive to a wavelength of 480 nm. Consequently, non-visual effects are more related to blue-light with respect to the other wavelengths. Figure 4.7 gives a synthetic representation of the five photo-receptors (a) and the wavelength sensitivity for each of them (b).

These important features of the natural light shall be considered not only when designing openings in buildings, but also when thinking about the electric light system. The actual reference standard framework includes CIE S026/E:2018[1] and DIN/TS 5031-100:2021[42].

For this purpose, the Equivalent Melanopic Lux (EML) is a metric used in WELL Certification[53] in order to measure the impact of light (mostly artificial one) on the circadian system. It considers the contribution of the five photo-receptors in the eye for the regulation of the circadian rhythms and the regulation (suppression or release) of the

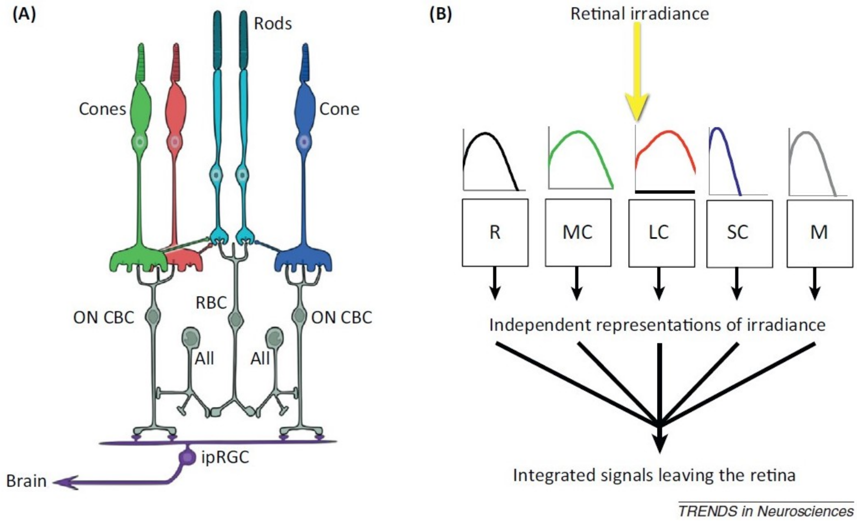


Figure 4.7: The five photo-receptors in the human eye (a) and their sensitivity to the light wavelengths (b). Image from[1]

hormone Melatonin[21]. It is computed as follows:

$$\mathrm{EML} = R \cdot L \tag{4.23}$$

where L is the expected (designed or measured) illuminance in the vertical plane at the eye cornea, while R is the melanopic ratio, i.e. how much a light source stimulates the human circadian system.

The term R is computed as the ratio between the Melanopic Irradiance (E_m) and the Photopic Irradiance (E_p), multiplied by CIE standard illuminant E constant ($E = 1.218$). To compute the first term is important to know the spectral power distribution (SPD) values for a specific light source. Then, every SPD value at each wavelength is multiplied by the value at the same wavelength of the Melanopic Action Spectra. The sum of these values gives the Melanopic Irradiance (E_m). Furthermore, the Photopic Irradiance is computed as the sum of the values obtained by the product between the SPD value at each wavelength and the value at the same wavelength of the visual action spectra. High R value is directly linked with high level of productivity.

Unified Glare Rating (UGR)

Glare is defined as "the condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme contrasts"[69]. There are two types of glare, the direct glare and the reflected one [Fig.4.8], and they can cause discomfort effects like loss of concentration, fatigue and the occurrence of mistakes. Several causes for glare can be identified as luminaires with no glare control, very bright or reflective surfaces, incorrect position of the workstation or incorrect luminaire arrangement.

In order to assess the glare risk from artificial light, the Unified Glare Rating is adopted

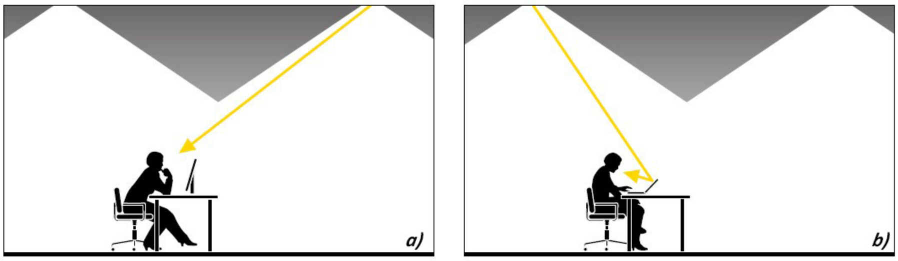


Figure 4.8: Types of glare that can occur in indoor spaces: direct glare (a) and reflected one (b). Image from [47]

by regulation and international standards such as EN 12464-1:2021[67]. It evaluates the glare that causes discomfort without necessarily impairing the vision of objects[3].

The UGR is based on a scale that normally ranges from 10, which indicates imperceptible levels of glare, to 30, that indicates intolerable levels of glare. It is an indicator for individual person[48] and it can be computed only for electric lighting sources, no daylight. The UGR is computed as follows:

$$\mathrm{UGR} = 8 \log_{10}(\frac{0.25}{L_b} \sum \frac{L^2 \omega}{p^2}) \tag{4.24}$$

where L_b is the background luminance(cd/m^2), L is the luminance of the luminous parts of each luminaire in the direction of the observer's eye (cd/m^2), ω is the solid angle of the luminous parts of each luminaire at the observer's eye (sr) and p is the Guth position index for each luminaire (displacement from the line of sight).

Color Rendering Index (CRI)

The Color Rendering Index (CRI) evaluates how accurately an artficial light source reproduces an object color, compared to a reference light source. The reference standard framework includes EN 12464-1:2021[67].

The reference source, that should have the same Correlate Color Temperature of the sample, could be a black-body curve if the Correlate Color Temperature (CCT) is below 5000K, while it is a CIE Daylight source if the CCT is above 5000K. A palette of specific eight colors(Fig.4.9) is used to measure the color differences between the reference source and the tested one and are indicated as ΔE_i. They represent the distance between each standard light point and reference light point. The Color Rendering Index is computed as follows:

$$R_i = 100 - 4.6 \Delta E_{UVW} \tag{4.25}$$

$$\mathrm{CRI} = R_a = \frac{1}{8} \sum R_i \tag{4.26}$$

where ΔE_{UWV} is the Euclidean distance (or the chromaticity coordinate value difference) on the color space CIE 1960 UCS between the standard light and the light source and R_i are the so called "special CRIs" calculated for every pair of chromaticity coordinates.

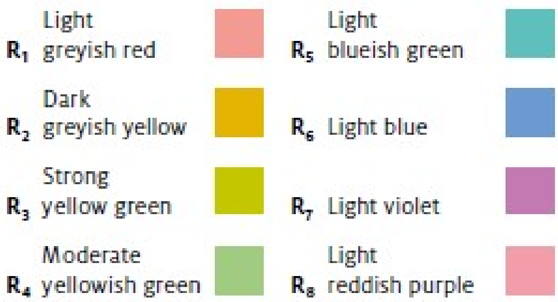


Figure 4.9: The eight test colors for the evaluation of the Color Rendering Index (CRI) of a light source. Image from[47]

This index can reach values from 0 to 100, where high values of CRI indicate a good correspondence between the reference colors and the tested ones. For instance, CRI value of 100 identifies the best possible faithfulness to a reference, while a CRI of 90 is considered excellent. Furthermore, a CRI value from 80 to 89 is considered as good and finally CRI comprised within 70 and 79 is considered acceptable.

Daylight Glare Probability (DGP)

The Daylight Glare Probability (DGP) is an index useful for the evaluation of glare risk from daylight. The reference standard framework includes EN 17037:2018[69] and it is used to evaluate protection from glare for spaces where the activities are comparable to reading, writing or using display devices and the occupants are not able to choose position and viewing direction. It is computed as follows:

$$\mathrm{DGP} = c_1 E_v + c_2 \log(1 + \sum \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{c4} \cdot P_i^2}) + c_3 \tag{4.27}$$

$$c_1 = 5.87 \cdot 10^{-5};\ c_2 = 9.18 \cdot 10^{-2};\ c_3 = 0.16;\ c_4 = 1.87 \tag{4.28}$$

Where E_v is the vertical illuminance at eye level (lux), L_s is the source's luminance (cd), ws is the solid angle of the source (sr) and P_i is the Guth position Index.

However, Simplified DGP (DGPs)[75] can be applied if no direct sun, or specular reflection of it, hits the eye of the observer, neglecting the influence of individual glare source:

$$\mathrm{DGPs} = (6.22 \cdot 10^{-5} \cdot E_v) + 0.184 \tag{4.29}$$

Moreover, Daylight Glare classes are defined in the Annex E of the EN 17037:2018[69], providing definition for the interpretation of the results obtained in indoor environments (see Table4.4).

Daylight Glare Index (DGI)

Another index to assess glare from natural light sources in interior spaces is the Daylight Glare Index. This metric can range from 10, which identify e level of glare which is just

Criterion	**DGP value**
Glare is mostly not-perceived	DGP ≤ 0.35
Glare is perceived but mostly not disturbing	$0.35 <$ DGP ≤ 0.40
Glare is perceived and often disturbing	$0.40 <$ DGP ≤ 0.45
Glare is mostly not-perceived	DGP ≥ 0.45

Table 4.4: Ranges for Daylight Glare Probability (DGP) values. Data are from[69]

perceptible, to 28, that corresponds to a level of glare perceived by occupants as just intolerable (Table4.5). According to [51], the first DGI was computed as follows:

$$GI = 10 \log \sum [\frac{B_s^{1.6} W^{0.8}}{B_b \cdot P}] \tag{4.30}$$

where B_s is the luminance (brightness) of each glaring light source within the occupant's field of view, W is the solid angle of the glare source at the eye level, B_b is the average luminance of the visual field and P is the position index.

Glare criterion corresponding to mean relation	Daylight Glare Index (DGI)
Just perceptible	10
Just acceptable	16
Just uncomfortable	22
Just intolerable	28

Table 4.5: Daylight Glare Index thresholds for glare assessment in interior spaces. Data are from[50].

Afterwards, the equation has been modified according to Ref.[27], thus the Daylight Glare Index can be computed as:

$$\text{DGI} = 10 \log[0.478 \sum_{i=1}^{n} (\frac{L_{s,i}^{1.6} \cdot w_{s,i}^{0.8}}{L_b + 0.07 w^{0.5} \cdot L_{win} \cdot P_i^{1.6}})] \tag{4.31}$$

where w is the solid angle related to each glare source and the observer's line of view, $L_{s,i}$ is the luminance of each source, L_b is the background luminance, i.e. for a window it is the average luminance of the wall excluding the window[29], L_{win} is the luminance of the window and P is the position index.

This metric is normally used to assess or predict glare from large sources like windows[29].

Table4.6 gives an interpretation of the DGI value with regard to the sensation experienced by the occupants. A DGI equal to 22 in considered the maximum acceptable value to avoid glare discomfort situation, even if in Ref.[50] a list of DGI recommended value are given depending on the space utilization type.

Location	DGI value
Classroom	16
Libraries	12
Staff rooms	12
Dressing room	22
Specialised rooms (art, needlework)	10
General offices	16
Drawing offices	12
Art galleries	10
Museums	16
Churches	10

Table 4.6: Limit values for Daylight Glare Index with respect to the location. Data are from[50].

Visual Comfort Probability (VCP)

The Visual Comfort Probability (VCP) is defined as the percentage of people that find a certain scene (viewpoint and direction) comfortable with regard to visual glare, and therefore is expressed as a number between 0 and 100[60].

To compute VCP, the Discomfort Glare Rating (DGR) must be calculated:

$$\mathrm{DGR} = (\sum_{i=1}^{n} \frac{Li \cdot Q_i}{L_{bs}^{0.44} \cdot P_i})^{n^{-0.0914}} \tag{4.32}$$

Where L_i is the average luminance of each glare source, L_{bs} is the average background luminance (including glare sources) as seen by the observer from the viewing position, n is the number of glare sources and Q_i is the solid angle factor for each glare source:

$$Q_i = 20.4\omega_i + 1.52\omega_i^{0.2} - 0.075 \tag{4.33}$$

Visual Comfort Probability is now computed as follows:

$$\mathrm{VCP} = \frac{100}{\sqrt{2\pi}} \int_{-\infty}^{6.374-1.3227ln(DGR)} \exp\left[\frac{-t^2}{2}\right] \mathrm{d}t \tag{4.34}$$

For interiors like offices, general design recommendations indicate that VCP should be more than 70, except in spaces with visual display terminals (VDTs) where it is recommended that VCP exceeds 80 for a direct lighting system. IESNA[29] proposed a numerical approximation for VCP computation:

$$\mathrm{VCP} = 279 - 110(\log_{10}\mathrm{DGR}) + C \tag{4.35}$$

$$C = \begin{cases} C = 0 & \text{if}\, 55 \leq \mathrm{DGR} \leq 200 \\ C = 350(\log_{10}\mathrm{DGR} - 2.08)^5 & \text{if}\, \mathrm{DGR} \leq 55 \wedge \mathrm{DGR} > 200 \end{cases} \tag{4.36}$$

Long-term indicators

Useful Daylight Illuminance (UDI)

The Useful Daylight Illuminance (UDI) is a long-term metric that corresponds to the percentage of the occupied time when a target range of illuminances at a point in a space is met by daylight[48]. It also can give information about the frequency of occurrence of excessive levels of daylight that can cause glare discomfort for the users or also solar gains for the interior spaces[29].

The UDI achieved is defined as the annual occurrence of daylight illuminances that can range between 100 and 3000 lux[26]. According to Ref.[26], this UDI range can be further subdivided into two sub-ranges as follows:

- *UDI-supplementary* [UDI-s], which gives the occurrence of daylight illuminances in the range of 100 to 300 lux. For this category, additional artificial lighting may be needed;
- *UDI – autonomous* [UDI-a], which gives the occurrence of daylight illuminances in range of 300 to 3000 lux. Thus, artificial lighting may not be needed.

Values that are out of UDI range are called *UDI fell-short* [UDI-f], when the illuminance is less than 100 lux and *UDI exceedance* [UDI-e], when the illuminance is greater than 3000 lux.

Spatial Daylight Autonomy (sDA)

In order to define the Spatial Daylight Autonomy (sDA) it is important to introduce at first what is Daylight Autonomy (DA). DA represents the percentage of annual daytime hours that daylight levels exceed a predefined illumination level[16]. It does not consider if the available daylight is too bright to use in the space and it is computed using a daylight simulation tool that computes the daylight levels in the space for every hour of the year.

$$\mathrm{DA} = \frac{\sum_i (wf_i \cdot t_i)}{\sum_i t_i} \in [0,1] \tag{4.37}$$

$$wf_i = \begin{cases} 1 & \text{if} E_{Daylight} \geq E_{Limit} \\ 0 & \text{if} E_{Daylight} < E_{Limit} \end{cases} \tag{4.38}$$

For what concerns the Spatial Daylight autonomy, it refers to the percentage of floor area where a given illuminance reference value is achieved for defined percentage of time regarding the entire workday. For this purpose, the simulation carried out for the computation, considers daylight levels and percentage of floor area, during the standard operating hours, i.e. from 8 a.m to 6 p.m[29].

$$\mathrm{sDA}_{x/y\%} = \frac{\sum_i (wf_i \cdot \mathrm{DA})}{\sum_i p_i} \in [0,1] \tag{4.39}$$

$$wf_i = \begin{cases} 1 & \text{if DA} \geq \text{DA}_{Limit} \\ 0 & \text{if DA} < \text{DA}_{Limit} \end{cases} \tag{4.40}$$

where x is the reference illuminance level, y is the time fraction, p_i are the points belonging to the calculation grid.

The reference standard framework includes LM-83-12[52] . Illuminating Engineering Society (IES) recommends sDA300/50 % for analysis of daylight sufficiency, expressing the percentage of points of the analyzed area which meet or exceed the horizontal illuminance threshold of 300 lx for at least 50 % of the occupied hours over a typical meteorological year.

4.1.4. Acoustic comfort

The exposure to noise can affect the quality of life and, in some extreme cases, it can lead to health problems. A good acoustical environment can provide for occupants the most suitable state of mind for a specific activity, together with a good environments for confidential conversation and no negative effect on health[44]. Indeed, the interior spaces shall be protected from the internal and external noise pollution sources, especially for the environments (e.g. schools, conference rooms, etc.) where the communication and the correct listening have a great importance.

Excessive noise exposure can have effects on hearing loss and various human body systems (e.g. cardiovascular, endocrine or nervous) leading to a sense of fatigue, interference with sleep rhythms and a reduction of productivity and work performance; on the other hand, the completely silence condition can led to a sense of estrangement[44].

4.2. How Indoor Environmental Quality can affect occupants' productivity

The lack of quality in interior spaces is directly related with the productivity levels and the health of the occupants, showing the occurrence of symptoms that can be associated to the Sick Building Syndrome (SBS) and higher costs for the entire building management and activities. In most cases, a poor indoor quality is more expensive than the amount for energy consumption for conditioning and ventilation, while the adoption of specific measures to improve IEQ could be highly cost-effective when considering the monetary savings derived from an improved health and productivity[57].

Productivity is based on the main concept of the ratio between the inputs and the outputs. It is often discussed referring to the labour productivity, intended as the market value of output per hour worked or per person employed[12].

4.2.1. Occupants' health and productivity

Ill-health condition can directly influence the productivity in workplaces. This is due to the phenomena of "absenteeism", in which people lose working days, and "presenteeism", where people decide to attend work when ill, experiencing reductions in their performance and productivity due to health conditions. In order to demonstrate that a large set of health conditions have been linked to reduced levels of productivity through the absenteeism and presenteeism phenomena, the authors of Ref.[24], in 2014, made a survey to employers of 82 UK companies that have chosen to participate at the competition for the "Britain's Healthiest Company". The results has showed that musculoskeletal disorders and hypertension are often linked with greater reductions in productivity and finally that reduction trend in productivity is directly proportional to the extent of the health concern. Other causes related to presenteeism and absenteeism are health risk behaviour like smoking or having a poor diet, because they can have the potential to raise the probability of adverse health outcomes[7]. One of the most relevant health risk behaviour is the amount of sleep. Indeed, in Ref.[24] the authors found that people who slept for less than five hours per night, reported 6.93 % greater productivity losses when working.

Another important role is covered by the relationship between productivity and mental health, intended by the World Health Organization (WHO) as the "state of well-being in which the individual realises his or her abilities, can cope with the normal stresses of life, work productively and fruitfully, and is able to make a contribution to his or her community"[7]. Mental health problems includes depression, anxiety or other conditions that can cause 13 % greater productivity losses in occupants subjected to this risk[24].

4.2.2. The Sick Building Syndrome

The Sick Building Syndrome (SBS) is a phenomenon that occurs in occupants of interior spaces with particular indoor conditions. It comprises a set of non-specific symptoms, such as upper-respiratory irritative symptoms, headaches, fatigue or rash, that can be responsible for absenteeism and presenteeism, as explained in the previous section, with a consequent decrease of the productivity[54]. This condition is different from the building-related illnesses, which are related to specific exposure in indoor spaces and normally to a single causal factor.

Although the type of symptoms can vary widely due to different causal factors in buildings, however some of them are commonly present such as irritation of mucous membranes and the upper respiratory tract, headache and lethargy[15]. Nevertheless, most common symptoms related to the Sick Building Syndrome can be divided into:

- *Mucous-membrane irritation*, such as eye irritation, throat irritation and cough;
- *Neurotoxic effects*, which includes headaches, fatigue, lack of concentration;
- *Respiratory symptoms*, like shortness of breath, cough and wheeze

- *Skin symptoms*, that includes rash, pruritus and dryness;
- *Chemosensory changes*, characterized by an enhanced or abnormal odour perception and visual disturbances.

Generally, symptoms related to the SBS start improving when the worker is away from the affected building or interior space, with of course different time period for the recovery.

The possible causes of Sick Building Syndrome can be sought in air contaminants, poor ventilation, bad thermal conditions or non-adequate lighting levels. Indoor air quality (IAQ) has an important role for the SBS phenomenon, due to the fact that people reported more sick building syndrome symptoms when they have perceived that the quality of air in interior spaces is poor. Indeed, air in enclosed spaces may be contaminated by chemicals from outdoor sources such as combustion products or gases, particulate matter and from indoor sources, like volatile organic compounds (VOCs), which are emitted generally from construction materials, furnishing, cleansing agents. Biological contaminants like pollen, bacteria, viruses, fungus or molds can pollute the indoor air through the stagnant water accumulated in humidifiers or conditioning systems. These air contaminants commonly cause fever, cough, muscles aches and allergic reaction[54].

Moreover, also thermal condition can affect occupants in buildings. Indeed, a temperature greater than 25°C can cause headaches and fatigue while a temperature lower than 18°C may be responsible for chills and flu-like symptoms[66]. Even humidity levels outside the range of $35-65\,\%$ can be related to adverse health effects, such as headaches, dizziness, favourable conditions for the growth of micro-organism, an increased rate of volatile organic compounds (VOCs) emission from construction materials or, on the other hand, dryness of the eye and stabilization of certain viruses (e.g. influenza)[66].

Beside the energy savings due to the use of natural light compared to the artificial one, daylight have important effects on human health. A poor illuminance in workplaces can lead to a sense of fatigue, headaches, eye strain[66] but also interfering in the biological sleep-awake rhythms (i.e. non-visual effects of light on the circadian system), causing effects on human health like depression or eating disorders.

In conclusion, indoor environmental factors regarding the thermal comfort, visual comfort and air quality can affect a lot the health of the occupants and workers. In Ref.[56] the authors have collected a set of some quantitative relation between the IEQ and the work performance. Thus, health concerns related to sick building syndrome may lead the possibility of absenteeism and presenteeism, directly correlated with losses in productivity standards, as explained in the first part of the chapter. For these reasons, building certification protocols started to develop, paying close attention to the indoor environmental features that can affect the quality of life, the health and users' well-being.

4.3. Certification for Health and Well-Being: The WELL Building Standard™

The WELL Building Standard™is a rating system developed by Delos and administrated by the International WELL Building Institute™(IWBI), which also collaborates with Green Business Certification Inc. (GBCI) for the certification part. It used to certify the health and well-being of the occupants in a building and at the moment is the first standard that its kind[53].

The new version now available, WELLv2™, is based on six main principles regarding the fairness, intended as to provide greatest benefits to the largest number of people; the flexibility of application throughout the world; the scientific nature, understood as a work supported by strong, validated research that lead to conclusions acceptable for the scientific community; the technical strength; the focus on the customer and finally the resilient behaviour with regards to the updates in scientific knowledge or technology field, adapting itself in a continuous way.

4.3.1. Project Types

The rating system provides two types of project:

- *Owner-occupied projects*, that represent buildings or interiors which are owned or rented by the project owner and regular occupants, such as employees. Thus, in this case the occupants are directly involved with the project owner.

- *WELL core projects*, that concern core and shell buildings and aim to implement fundamental features for tenants. Contrarily to the first type, these projects have the majority of regular occupants that are not involved with the project owner. If at least 75 % of the project area is occupied by tenants or is a common space accessible to all of them, the project should be registered as WELL Core. Mixed-use building should be assessed entirely with this project type only if at least 60 % of the area meets the requirements.

4.3.2. The WELLv2 architecture

This rating system is open to all types of building. Its structure is composed by ten concept and, for each of them, are defined *Preconditions* and *Optimizations*. Preconditions are mandatory features for the certification, while optimizations are optional pathways for project, in order to increase the WELL score.

The ten concepts

The structure of this type of certification is composed by a set of features that are grouped in ten "Concepts"[53]. These are the following:

- *Air*; in which the aim is to guarantee the indoor air quality by monitoring the concentration of pollutants in order to reduce or eliminate them and avoid the negative effects of a bad air quality during the entire lifetime of a building. This feature is composed by four preconditions and ten optimizations.
- *Water*; it is regarding quality, distribution and control of water in a building. it includes three preconditions and six optimizations.
- *Nourishment*; which requires the availability of fruits, vegetables and the nutritional transparency. It is composed by two preconditions and twelve optimizations.
- *Light*; which aims to create lighting environments in order to increase the exposure to lights (natural or artificial) and promote visual, mental and biological health. Biological health is intended as the reduction of stress, depression or metabolic disorders and the stimulus to the productivity respecting the circadian rhythms. It is composed by two preconditions and seven optimizations.
- *Movement*; which promotes physical activity. It includes two preconditions and nine optimizations.
- *Thermal comfort*; it aims to provide the highest level of thermal comfort in order to increase productivity and avoid symptoms related to the Sick Building Syndrome (SBS). Its features are divided in 1 precondition and eight optimizations.
- *Sound*; it supports health and well-being of the occupant paying attention to noises and sounds which can influence the activities in the built environment, in order to reduce/mitigate or eliminate them. It includes one precondition and eight optimizations.
- *Materials*; in which the aim is to avoid the exposure to chemicals that can have an impact for health. It promote the selection of construction material. Its features are divided in three preconditions and nine optimizations.
- *Mind*; it improves mental health through policy, program and design strategies that are related to what influences the cognitive and emotional well-being. It includes two preconditions and nine optimizations.
- *Community*; which promotes the implementation of design, policy and operations strategies that focus on addressing health disparities and promoting social diversity and inclusion. It is structured in four preconditions and fourteen optimizations.

These ten concepts are summarized in Fig.4.10.

4.3.3. Rating system

In WELLv2 certification, the weight assigned for each optimization depends on the sum of two main parts: its potential for impact, intended as how much a feature can affect or

Figure 4.10: The ten Concepts of WELL Building Standard ^{TM}. Image from[61]

promote the health and well-being, and its potential impact for the intervention.

Thus, the certification system uses a so called *dynamic scorecard* in which the environment can reach a maximum score of 12 points for each concept, but no more than 100 points across the ten concepts. Additional ten points ca be achieved for the concept "Innovation" which is a separate category in the rating system. It consists of the possibility to achieve more then 12 points per concept, submitting project features not already defined in that category. For each category a maximum of 1 point can be given for this reason.

Furthermore to obtain a certification the minimum points necessary are 40. The certification levels achievable are *WELL Bronze*, *WELL Silver*, *WELL Gold* and *WELL Platinum*, as showed in Table4.7.

WELL Certification		
Total points achieved	Minimum points per concept	Certification type
40 pts	0	WELL Bronze
50 pts	1	WELL Silver
60 pts	2	WELL Gold
80 pts	3	WELL Platinum
WELL Core Certification		
Total points achieved	Minimum points per concept	Certification type
40 pts	0	WELL Core Bronze
50 pts	0	WELL Core Silver
60 pts	0	WELL Core Gold
80 pts	0	WELL Core Platinum

Table 4.7: Thresholds for WELL Certification and WELL Core Certification. Data are from [53]

Pre-certification

The WELL certification system allows also the possibility to carried out the Precertification, a document in which the owner demonstrates a commitment in respect of possible future occupants' health and well-being. Thanks to this possibility, it is possible to understand which and how many features the project can really achieve during the effective performance verification process. The Precertification can be applied not only to building already built, but also to structures that are under the design phase, based on project plans rather than as-built conditions. To achieve the Precertification, the building or the project has to reach all preconditions and at least 40 points for the optimizations. Furthermore, the differentiation per certification type related to the achieved score is not available for this type of document[53].

Performance verification

The performance verification is the process for on-site assessment and testing. This is an important step for buildings in order to knowledge and the comprehension about the effective relationship between the built environment and the human health and well-being. Every performance verification process is carried out by a third-party expert called WELL Performance Testing Agent and the time spent for the assessment can ranges from one to three days, depending on the size and complexity of the construction. Normally, this verification consists of measurements, spot checks or performance evaluating tests that concern all the ten concepts[53].

5. The Smart Readiness Indicator

5.1. What is the Smart Readiness Indicator?

In 2018, the revised European Performance of Building Directive[40] introduced for the first time the concept of *Smart Readiness Indicator* (SRI). The aim was to underline the potential of Smart Technologies in the building sector, together with the improvement of the energy efficiency and the users' well-being. It is a voluntary European scheme for rating the smart readiness of buildings in order to make more concrete the concept of smartness to everyone: starting from owners, passing through service providers and ending up with final users.

Thus, the SRI should be a tool able to provide information about the technological readiness of a building, i.e. how it interacts with its occupants and the energy grids, while considering its capabilities for a more efficient operation phase and better performance through the use of *Information and Communication Technologies* (ICTs)[41]. In particular it evaluates the three key points expressed by the EPBD: the readiness to adapt in response to the needs of the occupants, the readiness to facilitate maintenance and efficient operation and the readiness to response to the situation of the energy grid [Fig. 5.1].

This set of properties makes the indicator an instrument both for residential and non-residential buildings, flexible enough to be applied in different climatic zones.

Figure 5.1: Three key functionalities of smart readiness in buildings. Image from[41]

Moreover, optimizing the energy efficiency control of technical building systems and enabling energy flexibility as part of their daily operation is the aim of smart buildings using ICT-based solutions and has the effect to reduce both the energy consumption of the building and its carbon footprint.

In conclusion, the aim of using this indicator is to promote building renovation and related investments to encourage the use of smart and energy efficient technologies across Europe.

In order to support the development of the SRI, two technical studies have been commissioned. The first one was launched in March 2017 in order to support the establishment of the SRI, while the second one started in December 2018 with the aim of providing the technical inputs necessary to refine the entire procedure for the SRI definition and computation framework. These works carried out useful tasks for developing a methodology for calculating the SRI, guided by principles concerning the technological neutrality for market actors (i.e. the definition of a solution with respect to its functional capability and not to the choice of some technological solutions), the ease of understanding, the transparency and tangibility of information, the inclusion of multiple distinct domains, a sufficient level of detail and reliability of the assessment together with the desire to limit the time and cost for it and, finally, the flexibility to contextual factors (e.g. building type, climate zone, etc.) and to the updates in order to support the innovation.

The results of the studies have led to a multi-criteria assessment method for calculating the SRI. Such a method is based on a catalogue of various smart ready services with various levels of smartness whose presence must be verified in the building. The mentioned services are divided into domains and each of them is related to impact criteria concerning the users and the energy grid.

Then, always starting from these two technical support studies, the Final Report is developed taking into account tasks from them. These ones are the following:

- Task 1, in which the consolidation of the definition and the calculation methodology of the SRI is discussed;
- Task 2, in which the SRI implementation pathways and the format of the SRI are investigated;
- Task 3, in which the guide line for the effective implementation of the SRI are given;
- Task 4, in which a quantitative modelling and analysis of the impact of the SRI at the EU level is carried out;
- Task 5, which includes the stakeholder consultation and the study website.

In the following sections Task 1 is explained more in depth with respect to the others, in order to give an exhaustive overview regarding the Smart Readiness Indicator and its methodological framework.

5.1.1. The structure of the SRI

The methodology adopted for the computation of the Smart Readiness Indicator is based on the assessment of defined smart ready services which can be present in a building. Then, they are divided in a set of nine domains that have impact on seven categories defined "Impact Criteria" by the methodology. Finally, these seven impact criteria are associated with the respective "Key Functionalities", which are requirements derived from the Energy Performance of Building Directive[40].

The Key Functionalities from EPBD

In the EPBD Directive were defined three key functionalities, that represent the base for the definition of the SRI[40]. According to [41] and Fig.5.1 they are:

- Ability to maintain energy efficiency performance and operation through the adaptation of energy consumption (e.g. use of energy from renewable sources);
- Ability to respond to the needs of the occupant, through the maintenance of a healthy and comfortable indoor environment, reporting energy use information maintaining user-friendly features;
- 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.

The seven impact criteria

In the final report about the SRI, seven impact criteria are defined under the three key functionalities, in order to better organize the structure of the methodology, the assignment of the score and the transparency with the final users. The definitions from the Final Report[41] are shown below.

For what concerns the first point "Energy savings and operation", the connected impact criteria are:

- "Energy saving", that refers to the impacts of the smart ready services on energy saving capabilities. It is not the whole energy performance of buildings that is considered, but only the contribution made to this by smart ready technologies, e.g. resulting from better control of room temperature settings;
- "Maintenance & fault prediction", in which automated fault detection and diagnosis has the potential to significantly improve maintenance and operation of technical building systems. It also has potential impacts on the energy performance of the technical building systems by detecting and diagnosing inefficient operation;

For the second key functionality "Respond to user need", the related impact criteria are:

- "Comfort", which refers to the impacts of services on occupant's comfort. Comfort is intended as 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", that refers to the impacts of services on the well-being and health of occupants. For instance, smarter controls can deliver an improved indoor air quality compared to traditional controls, thus raising occupants' well-being, with a commensurate impact on their health;
- "Information to Occupants", which refers to the impacts of services on the provision of information on building operation to occupants.

Finally, for the last key functionality "Respond to needs of the grid", is defined only the following domain:

- "Energy flexibility and storage", that refers to the impacts of services on the energy flexibility potential of the building. The study proposes to not solely focus on electricity grids, but also include flexibility offered to district heating and cooling grids.

All these information are summarized in Fig.5.2.

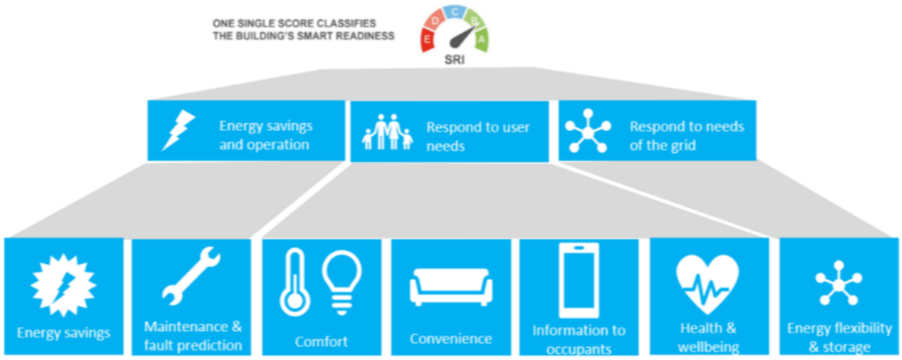


Figure 5.2: Seven impact criteria of Smart Readiness Indicator. Image from[41]

The nine domains, the smart services and the levels of functionality

Under each impact criteria, the contribute of nine domains are defined in percentage based on their influence for each category. The nine domains are:

- Heating;
- Domestic hot water;
- Cooling;
- Controlled ventilation;
- Lighting;
- Electricity;
- Dynamic Envelope;
- EV Charging;
- Monitoring & Control.

A synthetic view is given by the Fig.5.3 in which the structure previously presented is entirely shown.

Smart ready services are related to the way in which energy is generated, stored and used, how information about them are reported to the users and the type of control that

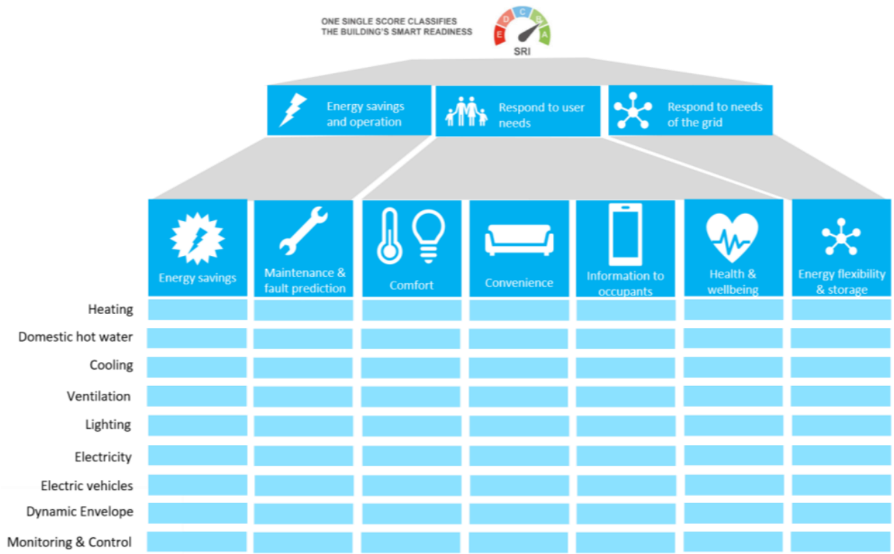


Figure 5.3: Proposed structure of domains and impacts criteria. Image from[41]

the user can have over the domain. For each smart ready service are defined levels of functionality in order to describe the level of smartness.

5.2. Assessment procedure

After the definition of how the SRI is structured, it is important to define the way in which this indicator shall be assessed. Some important considerations should be done.

The level of complexity of the assessment method is strictly linked with the time and the costs. For these reasons, three different methodologies are carried out from the Technical Support Studies: Method A, Method B and Method C.

However, at the moment only the first two are implemented, Method A and B, which are respectively the simplified method and the more complex one.

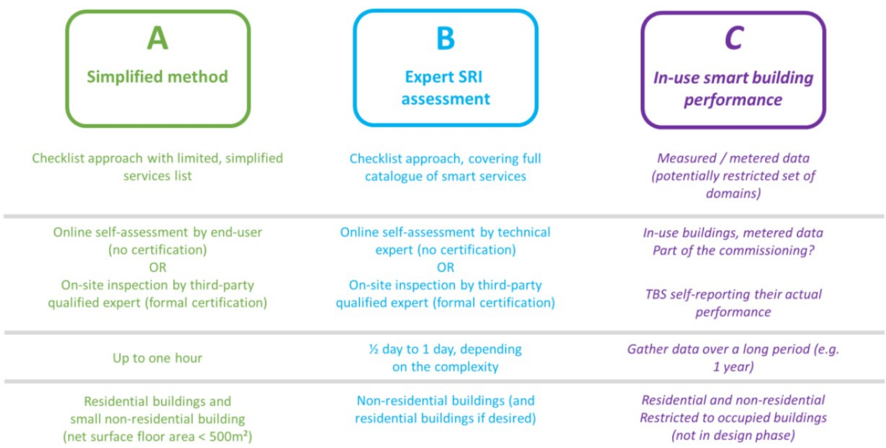


Figure 5.4: Three potential assessment method. Image from[41]

5.2.1. Methods A and B

The decision to provide two different types of assessment for the SRI is carried out from the Technical Support Studies, where questionnaire are send out to stakeholder. Different surveys are made in order to take a decision on which approach or approaches they prefer.

Analyzing more in depth this concept, stakeholder suggested that the assessment procedure should be pre-determined, based on specific conditions like the possibility to have two different type of evaluation: a light one for residential building or simple constructions, that also allows a self-assessment, and another one for more complex buildings or non-residential-ones in which a third-party is involved for the assessment procedure.

Method A, as mentioned before, is the simplified assessment procedure which consists in a checklist approach with a short catalogue composed by 27 smart services, defined in such a way that no expert knowledge is required and in order to cover the most relevant features for the SRI. The included smart services are structured and chosen considering the performance controllability, the storage and connectivity (intended as the ability to connect to or communicate with other TBSs, BACS or the energy grid) and reporting functionalities like performance, energy consumption or fault detection and prediction. The services related to each of the nine domains for the Method A are reported below in Fig.5.5.

Domain	Smart ready service
Heating	- Heat emission control - Heat generator control (all except heat pumps) - Heat generator control (heat pumps) - Storage and shifting of thermal energy - Report information regarding heating system performance
Domestic Hot Water	- Control of DHW storage charging (with direct electric heating or integrated electric heat pump) - Control of DHW storage charging - Report information regarding domestic hot water performance
Cooling	- Cooling emission control - Generator control for cooling - Flexibility and grid interaction - Report information regarding cooling system performance
Controlled ventilation	- Supply air flow control at the room level - Reporting information regarding IAQ
Lighting	- Occupancy control for indoor lighting
Dynamic building envelope	- Window solar shading control - Reporting information regarding performance
Electricity	- Storage of (locally generated) electricity - Reporting information regarding electricity consumption - Reporting information regarding local electrcity generation - Reporting information regarding energy storage
Electric vehicle charging	- Charging capacity - EV Charging Grid balancing - EV charging information and connectivity
Monitoring & Control	- Single platform that allows automated control & coordination between TBS + optimization of energy flow based on occupancy , weather and grid signals - Smart Grid Integration - Central reporting of TBS performance and energy use

Figure 5.5: SRI Method A: simplified service catalogue.

This method gives the possibility to make a free online self-assessment, in order to allow even family-homeowners to be able to evaluate their SRI. The third-party expert assessment is always possible. Moreover, the procedure is faster, because it takes less than one hour for a single family home and normally is used for residential buildings and non-residential with a limited surface floor area (less than $500\,\mathrm{m}^2$). Method A is useful in order to start providing first feedback and evaluation of the existing building stock, also for try to plan renovations and upgrades.

However, a formal certificate is emitted only if the assessment is done by a third-party expert. Online self-assessment is not considered valid in order to obtain a certification.

Method B is thought in order to give a formal assessment and provide a detailed view of a building's smartness compared to its maximum smartness potential. The checklist approach is the same used for Method A, but in this case the catalogue considered is the detailed one, with 54 smart ready services divided between the nine domains. The services related to each of the nine domains for the Method A are reported below in Fig.5.6. In Method B the on-site evaluation by a third-party expert is preferred and the time spent for the assessment is an half day or an entire one: it depends on the size and complexity of the building. Method B is normally used for non-residential building or residential one with a net surface floor area greater than $500\,\mathrm{m}^2$. Even if for particular cases the use of a method is better than the other, Method B is considered as the default one, applicable to all building types, new construction and existing buildings or retrofitting actions. A good point for this procedure is the fact that the possibility to make a self-assessment could provide accurate information about the real level of smartness and in which way the user could improve its score, without requiring costs for a formal assessment. However, to obtain the certification, a third-party evaluation is necessary.

A synthetic overview of all these information is given by the Fig.5.4 in which the main features of the Method A and Method B are reported.

5.2.2. Method C

The idea of a third assessment methodology for the Smart Readiness Indicator is born together with the creation of a Topical Group during the preparation of the Technical Support Report. The aim is to investigate the potential future evolution of the indicator, in particular an assessment procedure (also based on Method A and B) but using an automated approach. The most important features of this improved assessment are reported in Fig.5.5.

In this direction, Topical Group C proposed two improved pathways for the SRI: Automating Methods A and B and New Method C.

Automating methods A and B

Indeed in the future, for the two above-mentioned methods should be possible to self-report their functionality levels through the use of TBS and BACS. This evolution could reduce partially the costs and the efforts required for a third-party assessment, together with an improvement of the accuracy related to the evaluation.

In many buildings, thanks to the revised EPBD, will be introduced automation systems or more control options, with respect to the currently available. This will increase the use of the SRI able to generate automatically comparable indicators, helping the European market and supporting the process of improving the performance of the building stock.

Thus, this method should be the procedure for in-use smart buildings, while Method B and A remain in order to evaluate the buildings in the design phase.

New method C

The main difference from the previous method is that in this case the aim is to evolve the Smart Readiness Indicator up to a level in which it consists in a parameter able to quantify the building's impacts for the Three Key Functionalities and not only report functionality levels from a Smart Services Catalogue.

5.3. Calculation Methodology

The SRI calculation methodology is a multi-criteria assessment method that assigns a score in percentage, able to express how close or far the building is from the maximum degree of smart readiness. Thus, the higher the percentage is, the smarter the building[41]. Therefore, the main steps in this procedure can be summarized in Fig.5.7 where is represented the methodological framework with which the final score is obtained.

Starting from the smart ready services, that are related to every domain, is important to evaluate which of them are effectively present. This phase is the so-called "Triage process" and when doing it, is important to evaluate also which smart ready services may be omitted from the calculation process to avoid unfairly penalization, because of they can not be relevant for that building in a particular context (e.g. cooling system in specific European regions).

Afterwards, for each smart ready service, the level of functionality shall be assessed through a visual inspection or obtained from technical documentation. The domains' scores for each impact criteria are weighted using particular coefficient (i.e. the weighting factors) to obtain the final SRI score.

The entire procedure is explained more in depth in the following sections, analyzing all the steps necessary to compute the smart readiness indicator.

Domain	Smart ready service
Heating	- Heat emission control
	- Emission control for TABS (heating mode)
	- Control of distribution fluid temperature (supply or return air flow or water flow) - Similar function can be applied to the control of direct electric heating networks
	- Control of distribution pumps in networks
	- Thermal Energy Storage (TES) for building heating (excluding TABS)
	- Heat generator control (all except heat pumps)
	- Heat generator control (for heat pumps)
	- Sequencing in case of different heat generators
	- Report information regarding HEATING system performance
	- Flexibility and grid interaction
Domestic Hot Water	- Control of DHW storage charging (with direct electric heating or integrated electric heat pump)
	- Control of DHW storage charging (using hot water generation)
	- Control of DHW storage charging (with solar collector and supplymentary heat generation)
	- Sequencing in case of different DHW generators
	- Report information regarding domestic hot water performance
Cooling	- Cooling emission control
	- Emission control for TABS (cooling mode)
	- Control of distribution network chilled water temperature (supply or return)
	- Control of distribution pumps in networks
	- Interlock: avoiding simultaneous heating and cooling in the same room
	- Control of Thermal Energy Storage (TES) operation
	- Generator control for cooling
	- Sequencing of different cooling generators
	- Report information regarding cooling system performance
	- Flexibility and grid interaction
Controlled ventilation	- Supply air flow control at the room level
	- Air flow or pressure control at the air handler level
	- Heat recovery control: prevention of overheating
	- Supply air temperature control at the air handling unit level
	- Free cooling with mechanical ventilation system
	- Reporting information regarding IAQ
Lighting	- Occupancy control for indoor lighting
	- Control artificial lighting power based on daylight levels
Dynamic building envelope	- Window solar shading control
	- Window open/closed control, combined with HVAC system
	- Reporting information regarding performance of dynamic building envelope systems
Electricity	- Reporting information regarding local electricity generation
	- Storage of (locally generated) electricity
	- Optimizing self-consumption of locally generated electricity
	- Control of combined heat and power plant (CHP)
	- Support of (micro)grid operation modes
	- Reporting information regarding energy storage
	- Reporting information regarding electricity consumption
Electric vehicle charging	- EV Charging Capacity
	- EV Charging Grid balancing
	- EV charging information and connectivity
Monitoring & Control	- Run time management of HVAC systems
	- Detecting faults of technical building systems and providing support to the diagnosis of these faults
	- Occupancy detection: connected services
	- Central reporting of TBS performance and energy use
	- Smart Grid Integration
	- Reporting information regarding demand side management performance and operation
	- Override of DSM control
	- Single platform that allows automated control & coordination between TBS + optimization of energy flow based on occupancy, weather and grid signals

Figure 5.6: SRI Method B: detailed service catalogue.

5.3.1. Assessment of the smart ready services and the related functionality levels

Before starting, is important to establish which type of assessment shall be done. The available methods are the aforementioned Simplified Method A and the Detailed Method B. For each of them, a predefined number of smart ready services are available, 27 for the first one and 54 for the second, and are linked with the nine domains (i.e. a series of services compose the domain)[41].

A smart ready service is defined by a combination of smart ready technologies, defined in their part in a neutral technological way, with expected impacts on building users and the energy grid[41]. Each smart ready service is assessed individually and the corresponding functionality level is evaluated, based on what the service is able to provide. The latter can have influence on impact criteria through ordinal scores assigned based on how much

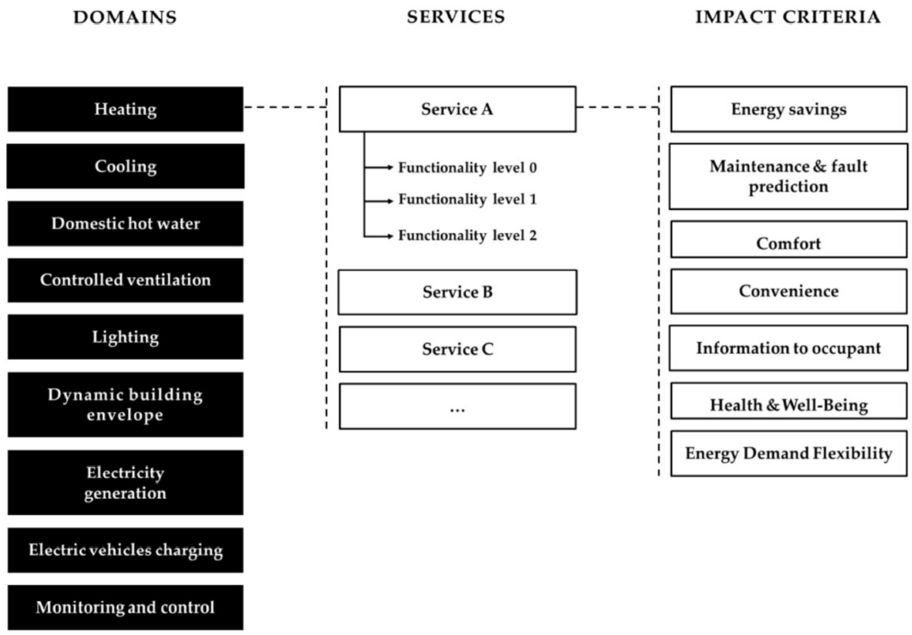


Figure 5.7: Methodological framework for the computation of the Smart Readiness Indicator (SRI). Image from[19]

smarter is that level compared to another: the higher the score, the higher the level of smartness. Therefore, every level of functionality is related to the seven impact criteria through the assignment of a score. This score is computed using the following equation:

$$I(d, ic) = \sum_{i=1}^{N_d} I_{ic}(FL(S_{i,d})) \tag{5.1}$$

where d is the number of the technical domain analyzed, ic is the number of the impact criterion in question, N_d is the total number of services in the analyzed technical domain d, $S_{i,d}$ is the service i of the technical domain$d$, $FL(S_{i,d})$ is the impact criterion score of the related smart service $S_{i,d}$ available in the building, $I_{ic}(FL(S_{i,d}))$ is the impact criterion score of the related service $S_{i,d}$ for the impact criterion number ic, according to the service's functionality level and finally, *I(d,ic)* is the impact criterion score of domain number d for impact criterion number ic.

5.3.2. Vertical aggregation: the domain level

The aforementioned ordinal scores, related to the level of functionality assessed and referred to the impact criteria, are aggregated as a unique domain score.

Doing that, every domain has a total score for each impact criteria, i.e. the domain impact score. Such domain score is computed as the ratio between the domains' service individual score and the theoretical maximum score achievable for each of them, as showed in Fig.5.9.

Finally, for each impact criterion is computed the total impact score through a weighted sum, based on the importance that each domain has on the seven impact criteria.

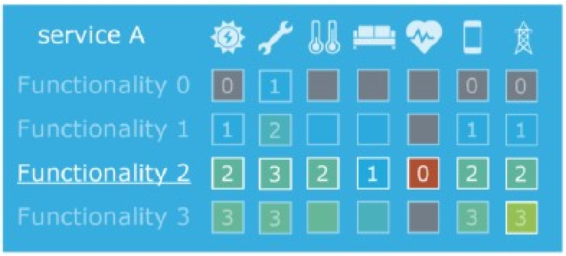


Figure 5.8: Matrix of the impact score related to each impact criteria of an hypothetical smart ready service: in this case is assumed that the functionality level 2 is the one present in the building. Image from[41]

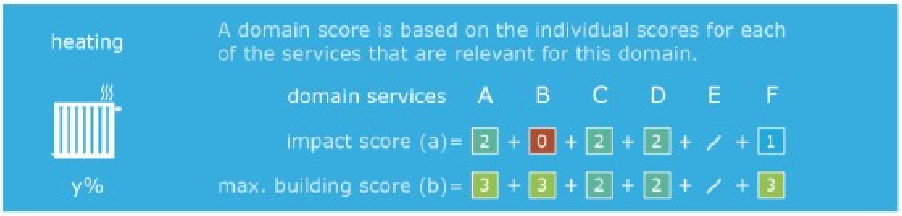


Figure 5.9: Example of domain score computation. Image from[41]

Therefore, every impact category has its own score due to the vertical aggregation, computed as follows:

$$SR_{ic} = \frac{\sum_{d=1}^{N} W_{d,ic} \cdot I_{d,ic}}{\sum_{d=1}^{N} W_{d,ic} \cdot I_{d,ic}} \cdot 100 \tag{5.2}$$

where d is the number of technical domain analyzed, N is the total number of technical domains, $W_{d,ic}$ is the weighting factor expressed as a percentage of technical domain number d for impact criterion number ic and SR_{ic} is the smart readiness score expressed as a percentage for impact criterion number ic.

The weighting factor applied depends on the type of building, i.e. residential or non-residential, the climate zone (e.g. North Europe) and other characteristics. Such weighting factors are established by the methodology and can be divided into three types: fixed weights, equal weights and energy balance ones. More information about these weighting factors are given in a following section.

5.3.3. The horizontal aggregation and the final SRI value

In order to obtain a final real score for the Smart Readiness Indicator, an horizontal aggregation shall be applied. In this case, the aggregation is done for every impact criteria, with a view to obtain an overall score for the three key functionalities. As explained for the total impact score, such overall impact score is obtained as a weighted sum, in which weights depend on the relative importance of the impact criterion considered. It can be computed as follows:

$$N = A \cdot a + B \cdot b + C \cdot c + D \cdot d + E \cdot e + F \cdot f + G \cdot g \tag{5.3}$$

where N is the total impact score, weighted score by domain; A is the impact score (from 0 to 100) for the impact criterion "Energy savings" while a is the related impact weighting (from 0 to 100 %); B is the impact score (from 0 to 100) for the impact criterion "Energy flexibility and Storage" while b is the related impact weighting (from 0 to 100 %); C is the impact score (from 0 to 100) for the impact criterion "Comfort" while c is the related impact weighting (from 0 to 100 %); D is the impact score (from 0 to 100) for the impact criterion "Convenience" while d is the related impact weighting (from 0 to 100 %); E is the impact score (from 0 to 100) for the impact criterion "Health and Well-being" while e is the related impact weighting (from 0 to 100 %); F is the impact score (from 0 to 100) for the impact criterion "Information to occupants" while f is the related impact weighting (from 0 to 100 %) and G is the impact score (from 0 to 100) for the impact criterion "Maintenance and Fault prediction" while g is the related impact weighting (from 0 to 100 %). Furthermore, the final SRI score, expressed in percentage, is computed with the ratio between the overall impact score and the theoretical maximum overall impact score obtainable for the building:

$$SRI = \frac{\text{Total real score}}{\text{Theoretical max score}}[\%] \tag{5.4}$$

Therefore, the final SRI value represents an overall percentage of the maximum obtainable score for that building.

However, the Smart Readiness Indicator can be expressed as a total percentage, that brings together the contributions for all sub-categories (i.e. domains and impact criteria) or even expressed in a disaggregated way, with a percentage for each impact criterion that can easily express the contribution of every part of the SRI. The Smart Readiness Indicator can furthermore be expressed with a class, that ranges from A to G based on the score achieved[32].

SRI	Class
$> 86\,\%$	A
$> 72\,\%$	B
$> 58\,\%$	C
$> 44\,\%$	D
$> 30\,\%$	E
$> 16\,\%$	F
$> 16\,\%$ or less	G

Table 5.1: Conversion of the Smart Readiness Indicator score into classes. Data are from [32].

5.4. How weighting factors are determined in the SRI methodology

At the three levels, different types of weights are applied based on the importance of each category with respect to the others. In this part, is described the methodology used by the Final Report[41] to determine all the weighting factors used for the computation of the Smart Readiness Indicator.

For these purpose, a differentiation is done for some weightings, based on the type of building and the climate zone. Indeed, buildings can be identified as "Residential" or "Non-residential" but for the latter, no more differentiation is done based on the specific type (e.g. offices, healthcare, etc.) because of insufficient data are currently available[41]. Furthermore, with regards to the geographical context, five climate zones are identified: Northern Europe, Western Europe, Southern Europe, North-Eastern Europe and South-Eastern Europe. Three approaches for the determination of the weighting factors are adopted. The first one is based on the concept of "equal weightings", where equal weights are given to each category; the second approach is based on the "predicted impact" in which a weighting scheme is prescribed in order to reflects the estimated impact of a particular category with respect to the others. Finally, the third approach is the so-called "energy balance", in which the weight given to a particular service reflects the importance of that service in the overall energy use of the building[41].

5.4.1. Starting point: the three key functionalities in the EPBD Directive

As stated previously, the SRI methodology is based on the EPBD Directive, in which were defined three main capabilities of such indicator, the so-called "key functionalities", that represent the starting point for the development of the Smart Readiness Indicator[41]. Therefore, they are reported below:

- Ability to maintain energy efficiency performance and operation through the adaptation of energy consumption;
- Response to the needs of the occupant;
- Flexibility of a building's overall electricity demand.

These three points are considered equal in weight for the SRI methodology, in order to respect the intent of the EPBD in which these three requirements have the same importance.

Thus, the SRI methodology assigned a weighting factor equal to 1/3 for each key capability; i.e., each score will be 33.3 % of the total [Fig. 5.10].

Figure 5.10: Weighting factors assigned to the 3 Key Functionalities in the SRI methodology. Image From[41].

5.4.2. The seven impact criteria

The seven Impact Criteria defined under the three key functionalities are weighted equally between the ones belonging to the same main capability. For what concerns the first key

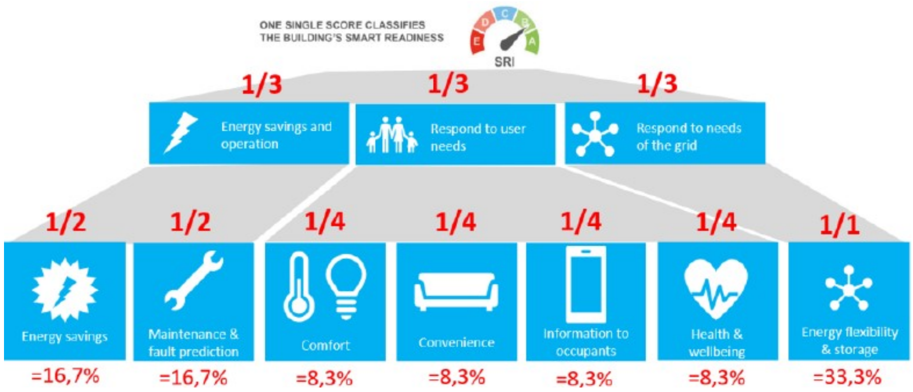


Figure 5.11: Weighting factors assigned to the seven Impact Criteria in the SRI methodology. Image From[41].

functionality, the connected impact criteria are "Energy saving" and "Maintenance & fault prediction". For such criteria are assigned the same weights, so 1/2; i.e., the each impact will be 16.7 % of the total [Fig. 5.11].

For "Respond to user needs" are defined four impact criteria, which are "Comfort", "Convenience", "Information to occupants" and "Health & Well-being". Also in this case, for each impact criterion is assigned the same weight, equal to 1/4; i.e., each impact will be 8.3 % of the total.

For the last key functionality is defined only one impact criterion, which is "Energy flexibility & storage" and count as the 33.3 % of the total [Fig. 5.11].

5.4.3. The nine domains

As seen in the previous section, the SRI is based on a weighted sum regarding the domain and the impact criteria levels. The determination of the weighting factors at the domains level takes into account the aforementioned three different methods:

- The *predicted impact approach*; in which for those domains that are not directly linked to energy balance (e.g. monitoring & control), a weighting factor can be defined based on the estimated impact of that domain[41]. This approach determine "fixed values", assigned to some domains, for all the impact criteria; i.e. a 20 % weighting is assigned to the domain “monitoring and control” for all impact criteria [Fig5.12];

- The *equal weighting*; after the definition of fixed values, these weighting factors are obtained by dividing in equal percentage the remaining values of other domains for each impact criterion as follows:

$$f_{d,ic} = \frac{100\% - \sum w_{fixed}}{N_{domain}} \tag{5.5}$$

For instance:

$$f_{HEAT,Comf} = \frac{(1 - f_{MC,conf})}{\text{number of relevant domains}} \tag{5.6}$$

$$f_{HEAT,comf} = \frac{(1 - 0.20)}{5} = 0.16 \tag{5.7}$$

where $f_{d,ic}$ is the weighting factor for a given domain and impact criterion and N_{domain} is the number of relevant domain for that impact criterion (excluded the domain with fixed weights).

Equal weightings by domain are applied for those impact criteria where there is currently no information on the relative importance of different domains to the impact criterion in question[31].

- The *energy balance approach*; these values depend on the climate zone or building type and they are the only that can be changed when using an alternative energy balance or data from a certification. The definition process is quite similar to the Equal weights but, in this case, the percentages are assigned in relation with the relative importance of the examined domain. An example is given below, in order to quantify the equal values for all domains in a specific impact category [Fig.5.12].

$$f_{d,ic} = (100\% - \sum(\text{fixed weights})) \cdot \alpha_{domain} \tag{5.8}$$

where $f_{d,ic}$ is the weighting factor for a given domain and impact criterion and α_{domain} is the relative importance of the considered domain. The relative importance of a domain α_{domain} could be predetermined using tables from the SRI methodology [Tab.5.2] or it is possible to compute it by using data from EPC certification or other energy balance[41]. The calculation method is explained below:

$$\alpha_{domain} = \frac{Q_{domain}}{Q_{total}} \tag{5.9}$$

$$Q_{total} = Q_{HEAT} + Q_{COOL} + Q_{DHW} + Q_{VENT} + Q_{LIGHT} + Q_{RENEW} \tag{5.10}$$

where Q_{domain} is the primary energy use for the considered domain, Q_{HEAT} is the primary energy use for space heating of the considered building, Q_{COOL} is the primary energy use for space cooling of the given building, Q_{DHW} is the primary energy use for domestic hot water, Q_{VENT} is the primary energy use for ventilation, Q_{LIGHT} is the primary energy use for lighting and finally Q_{RENEW} is the renewable energy produced on site, expressed as primary energy[41].

Residential Buildings					
Domain	North	West	South	North-East	South-East
Heating	39.9	45.3	42.2	40.5	27.5
DHW	12.4	10.2	13.3	18.6	7.7
Cooling	0.0	4.1	9.2	0.0	19.5
Ventilation	25.0	23.8	12.3	25.4	14.4
Lighting	4.9	2.0	3.6	0.8	1.2
Electricity	17.8	14.8	19.5	14.7	29.6
Non-residential Buildings					
Domain	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

Table 5.2: Relative importance of domains (α_{domain}) by climate zone, for residential and non-residential buildings. Data are from [41].

In Fig.5.12 are summarized all the types of value given by the Final Report[41] about the SRI methodology. All the values under the red shape are the "Fixed" ones; while the weighting factors under the yellow shape and the green shape are respectively the "Equal" and the "Energy balance" ones. The white spaces under each impact criterion mean that no value is assigned for that domain in that impact category.

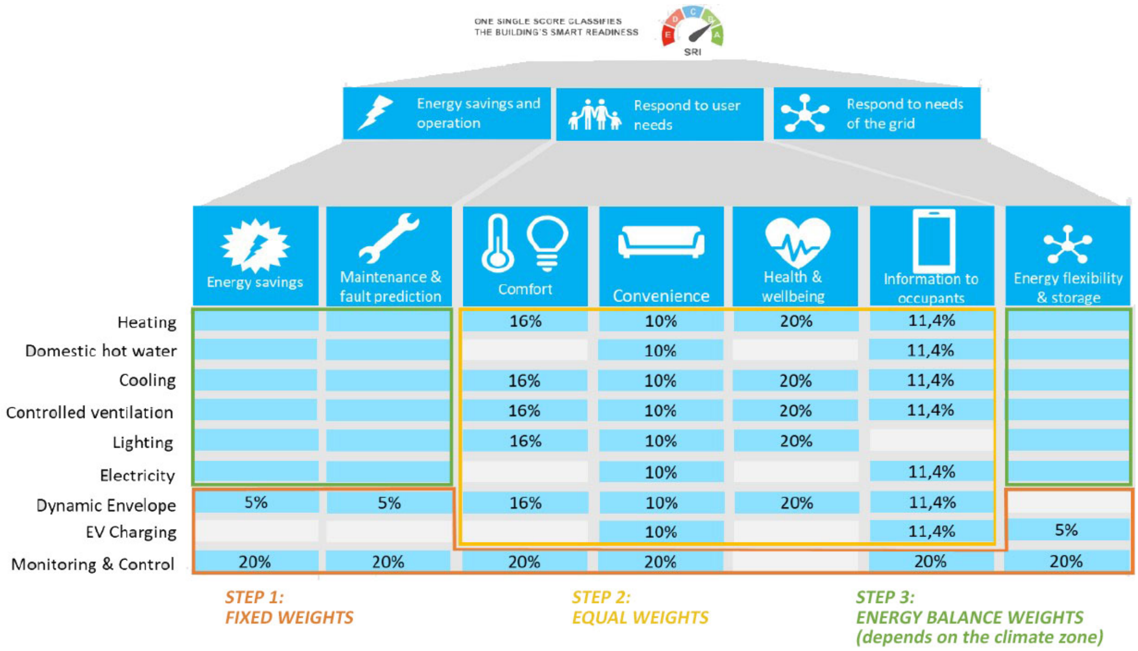


Figure 5.12: The three proposed approach for the determination of the domains' weighting factors. Image from[41]

6. Critical analysis on future developments for the Smart Readiness Indicator focusing on the functionality "Respond to users need"

In this chapter the thesis work is presented and developed with a focus on the part concerning the SRI's key functionality "Respond to users' need". In the first section is proposed a new scoring methodology for assessing the level of a set of smart ready services that can be adopted in a building or a building unit.

This new proposal is developed relying on the computation of the KPIs presented in Chapter 4 to assess the impact of each service on the criteria "Comfort" and "Health and Well-being". The impact is scored using ranges given from regulations and literature review.

Afterwards, in the second section of this chapter, the weighting factors actually used for the Smart Readiness Indicator are revised using the Analytic Hierarchy Process. For this purpose, a survey is prepared and proposed to a group of architects, engineer and experts in this field. The results are processed to obtain the new weightings for the methodology and to better reflect the real importance of criteria and domains for specific climate conditions and types of space.

6.1. A reviewed scoring methodology for the SRI: KPIs calculation to assess the impact of smart ready services on Indoor Environmental Quality

The scoring system defined and adopted in the Final Report about the Smart Readiness Indicator[41] uses the service's level of functionalities to determine the impact on the seven Impact Criteria. Thus, for each domain the overall score depends only on the automation degree of services implemented into the building. This procedure can lead to a possible overestimation or underestimation of the effective indoor conditions that have impact on "Comfort" and "Health and Well-being" criteria in the SRI.

With the aim to improve this situation, a new scoring methodology is proposed. Impacts on "Comfort" and "Health and Well-being" are computed using not only the functionality levels but also Key Performance Indicators related to IEQ. This KPIs assume values depending on the indoor environmental conditions and are rated using tables from Standards and Regulation or normalizing the obtained value into a score that ranges from 0 to 3. Such a range is chosen in order to maintain the SRI score configuration and the overall score is computed as the arithmetic mean between the score assigned for the level of functionality and the score reached from the KPIs evaluation.

This reviewed scoring system has led to the development of two new assessment methods related to the operation phase of the building. They are presented as two possible ways for the Method C development, one using instantaneous data from the building and called Steady-state assessment, and one using data recorded at the end of a time-period or a season, defined as Long-term assessment. The first one is characterized by a dynamic SRI score that can vary over time depending on the sampling time-step, e.g. every hour, according to the indoor conditions during the considered period. On the other hand, the Long-term assessment is characterized by an SRI value that takes into account the indoor conditions over a time-period.

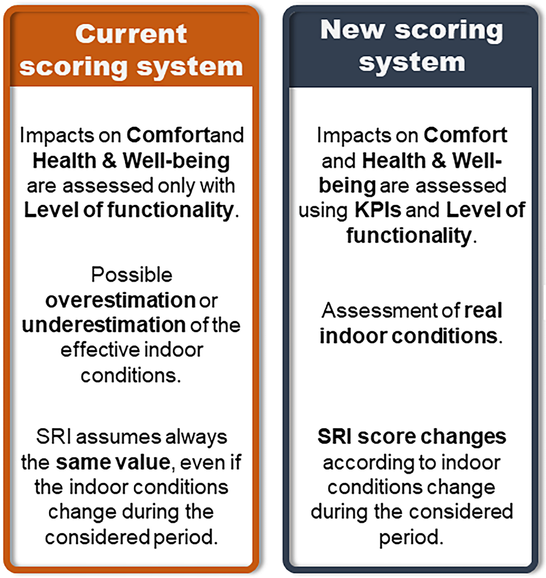


Figure 6.1: Comparison between the scoring methodology actually implemented for the SRI and the new proposed one.

6.1.1. Key Performance Indicator for the SRI methodology

In the next sections the selected KPIs for the new scoring system are presented with their scoring ranges. All these indicators are proposed for SRI domains of Heating, Cooling, Controlled ventilation, Lighting and Dynamic envelope, thus for each domain that has impact on "Comfort" and "Health and Well-being".

6.1.2. Steady-state evaluation

The Steady-state assessment has been studied and proposed with the aim of evaluating the Smart Readiness Indicator instantaneously, at pre-defined time-step (e.g. every hour) obtaining a dynamic SRI score that is able to report the currently performance. This can be done considering the effective indoor conditions through the use of the proposed short-term KPIs. Table6.1 gives an overview of all the indices proposed for this SRI assessment.

Short-term KPIs

KPI	SRI associated domain	SRI associated Impact Criteria	Reference
Predicted Mean Vote (PMV)	Heating, Cooling	Comfort	EN 16798-1:2019[68], ISO 7730:2005[71]
Predicted Percentage of Dissatisfied (PPD)	Heating, Cooling	Comfort	EN 16798-1:2019[68], ISO 7730:2005[71]
Operative temperature	Heating, Cooling	Health & Well-being	EN 16798-1:2019[68], ISO 7730:2005[71]
Air speed	Controlled ventilation	Comfort	EN16798-1:2019[68], ISO 7730:2005[71]
CO2 concentration	Controlled ventilation	Health	EN16798-1:2019[68]
Unified Glare Rating (UGR)	Lighting	Comfort	EN 12464-1:2021[67]
Visual Comfort Probability (VCP)	Lighting	Comfort	Mistrick[60]
Color Rendering Index (CRI)	Lighting	Comfort	EN 12464-1:2021[67]
Equivaent Melanopic Lux (EML)	Lighting	Health & Well-being	WELLv2[53]
Daylight Factor (DF)	Dynamic Envelope	Comfort	EN 17037:2018[69]
Daylight Glare Index (DGI)	Dynamic Envelope	Health & Well-being	EN 17037:2018[69]
Daylight Glare Probability (DGP)	Dynamic Envelope	Health	EN 17037:2018[69]

Table 6.1: Short-term Key Performance Indicators for the SRI steady-state assessment.

Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)

The Fanger's KPIs Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) are defined to evaluate impacts on "Comfort" for services belonging to Domains like Heating and Cooling. In particular, considering the simplified services catalogue from SRI methodology, these services are Heating-S1, S2 a-b and Cooling-S1, S2 and S3.

The ranges for this two indices are defined using tables and thresholds given by Standards like EN 16798-1:2019 and ISO 7730:2005. This ranges are converted into a score from 0 to 3, according to Tables6.2.

Class	PMV Range	PPD Range	Score
I	$-0.2 \leq \text{PMV} \leq 0.2$	$< 6\,\%$	3
II	$-0.5 \leq \text{PMV} \leq 0.5$	$< 10\,\%$	2
III	$-0.7 \leq \text{PMV} \leq 0.7$	$< 15\,\%$	1
IV	$> 0.7 \wedge \text{PMV} < -0.7$	$> 15\,\%$	0

Table 6.2: Scoring table for PMV and PPD indices. Data are from[68][71].

The overall score for this part is computed as an arithmetic mean between the scores reached by each Key Performance Indicator.

Operative temperature

The Operative temperature is chosen to evaluate impacts on "Health and Well-being" for services under the technical domains like Heating and Cooling. In particular, considering the simplified services catalogue from SRI methodology, these services are Heating-S1, S2 a-b and Cooling-S1, S2 and S3.

The ranges proposed for the SRI scoring methodology refers to what stated by the Standards EN 16798-1:2019 and ISO 7730:2005, where both for the heating and cooling season, are provided the main classes, from the higher to the lower one in terms of requirements and comfort, with the related temperature range. For each of them is proposed a score that reflects the performance level implemented in the interior space.

Heating season			Cooling season		
Class	Range	Score	Class	Range	Score
I	$22 \pm 1\,°\text{C}$	3	I	$24.5 \pm 1\,°\text{C}$	3
II	$22 \pm 2\,°\text{C}$	2	II	$24.5 \pm 1.5\,°\text{C}$	2
III	$22 \pm 3\,°\text{C}$	1	III	$24.5 \pm 2.5\,°\text{C}$	1
IV	$> 22 \pm 3\,°\text{C}$	0	IV	$> 24.5 \pm 2.5\,°\text{C}$	0

Table 6.3: Scoring table for operative temperature index. Data are from[68][71].

Air speed

For services defined under the "Controlled ventilation" domain, the impact assessment on "Comfort" criteria are evaluated using the Air speed index. In this case, always considering the simplified services catalogue, the service involved is only one and corresponds to Controlled Ventilation-S1.

Once again, the ranges adopted to define the KPI's scores are essentially from the EN 16798-1:2019 and ISO 7730:2005. They are divided in ranges adopted during the heating season and the ones adopted during the cooling period. The criterion used for the score determination assigns to the best performance level the higher score, as showed in Table6.4.

Heating season			Cooling season		
Class	Range	Score	Class	Range	Score
I	$< 0.10\,\mathrm{m/s}$	3	I	$< 0.12\,\mathrm{m/s}$	3
II	$0.10\,\mathrm{m/s} < v < 0.16\,\mathrm{m/s}$	2	II	$0.12\,\mathrm{m/s} < v < 0.19\,\mathrm{m/s}$	2
III	$0.16\,\mathrm{m/s} < v < 0.21\,\mathrm{m/s}$	1	III	$0.19\,\mathrm{m/s} < v < 0.24\,\mathrm{m/s}$	1
IV	$> 21\,\mathrm{m/s}$	0	IV	$> 24\,\mathrm{m/s}$	0

Table 6.4: Scoring table for air speed index. Data are from[68][71].

CO_2 concentration

Class	Range	Score
I	$< 550\,\mathrm{ppm}$	3
II	$550\,\mathrm{ppm} < CO_2 < 800\,\mathrm{ppm}$	2
III	$800\,\mathrm{ppm} < CO_2 < 1350\,\mathrm{ppm}$	1
IV	$> 1350\,\mathrm{ppm}$	0

Table 6.5: Scoring table for $CO_2$2 concentration index. Data are from[68][71].

To evaluate the impacts on "Health and Well-being" concerning the Indoor Air Quality and the related services under the "Controlled ventilation" domain, it has been decided to use the indoor CO_2 concentration. The ranges for the scoring assessment are provided by the EN 19798-1:2019 and includes four main classes, from the better (class I) to the worst one (class IV). Consequently, the better is the class, the higher the score, as showed in Table6.5.

Unified Glare Rating (UGR), Visual Comfort Probability (VCP) and Color Rendering Index (CRI)

For services defined under the "Lighting" domain, the impact assessment on "Comfort" criteria are evaluated using three different indices: the Unified Glare Rating (UGR), the

Visual Comfort Probability (VCP) and the Color Rendering Index (CRI). In this case, always considering the simplified services catalogue, the service involved is only Lighting-S1.

Standards and regulation do not define tables with classes and ranges, but provide limit thresholds for acceptability based on the type of activity or the type of space. For instance, UGR can range from 5 to 30 but, according to EN 12464-1:2021, for offices the maximum allowable value is set at 19. Consequently, the score is defined normalizing the obtained value from 0 to 3, using the following equation:

$$\text{score}_{normalized} = \frac{(val_{obs} - val_{min}) \cdot (3 - 0)}{(val_{max} - val_{min})} \tag{6.1}$$

Where val_{obs} is the KPI value obtained from the evaluation of indoor conditions, while $val_{limit,min}$ and $val_{limit,max}$ are respectively the minimum and maximum value that the index can reach. Even for CRI and VCP there are no ranges from Regulations and Standards, thus the same procedure is applied to them. For what concerns the Color Rendering Index, the EN 12464-1:2021 sets as a minimum acceptable value for indoor spaces like offices 80. On the other hand, VCP can range from 0 to 100, but the minimum value is set at 60 to avoid occupants' discomfort. In Table6.6 are reported the maximum and minimum limit values for the three aforementioned KPIs.

KPI	$\text{val}_{limit,min}$	$\text{val}_{limit,max}$
Unified Glare Rating (UGR)	19	5
Visual Comfort Probability (VCP)	60	100
Color Rendering Index (CRI)	80	100

Table 6.6: Maximum and minimum limit values for UGR, VCP and CRI indices for the score normalization procedure.

The overall score for this part is computed as an arithmetic mean between the scores reached by each Key Performance Indicator.

Equivalent Melanopic Lux (EML)

For services defined under the "Lighting" domain, the SRI methodology does not provide impacts on "Health and Well-being". However, studying in depth the state-of-art regarding the effects on human health due to light, it was found that not only natural light but also artificial one can affect the circadian rhythms in every-day life. Therefore, the Equivalent Melanopic Lux (EML) is proposed as KPI for the assessment of impacts related to health.

Standards and regulation do not define tables with classes and ranges, but the WELL v2 Certification provides limit values in its rating scheme[53]. For this scoring methodology EML can range from 0 to 275 which is the value set by the WELL Certification under the feature "Circadian Lighting Design" in the "Light" concept. The final score is obtained normalizing the EML value between 0 and 3 using the Equation6.1.

Daylight Factor (DF)

To evaluate the impacts on "Comfort" concerning services under the "Dynamic envelope" domain, it has been decided to use the Daylight Factor (DF).

According to tables and ranges defined in EN 17037:2018, the scores are assigned depending on the performance level reached in the indoor environment compared to a Daylight target (DT), as showed in Table6.7. This ranges are computed using value provided by the standards for Italian locations.

Class	Daylight Target DT	Range	Score
I	750 lux	DF $> 4\,\%$	3
II	500 lux	$2.6\,\% <$ DF $< 4\,\%$	2
III	300 lux	$1.6\,\% <$ DF $< 2.6\,\%$	1
IV	< 300 lux	DF $< 1.6\,\%$	0

Table 6.7: Scoring table for Daylight Factor (DF). Data are referred to Italy and are from[69].

Daylight Glare Probability (DGP) and Daylight Glare Index (DGI)

For services defined under the "Dynamic envelope" domain, the impact assessment on "Health and Well-being" criteria are evaluated using the Daylight Glare Probability (DGP) and the Daylight Glare Index (DGI). In this case, always considering the simplified services catalogue, the service involved corresponds to Dynamic envelope-S1.

The ranges adopted to define the DGP scores are essentially from the EN 17037:2018 and are established relying on the glare sensation, due to natural light, experienced by the occupants in the interior space. The criterion used for the score determination assigns to the best performance level the higher score, as showed in Table6.8.

Class	Range	Score
I	< 0.35	3
II	$0.35 <$ DGP < 0.40	2
III	$0.40 <$ DGP < 0.45	1
IV	> 0.45	0

Table 6.8: Scoring table for Daylight Glare Probability (DGP). Data are from[69].

On the other hand, for what concerns score assigned to DGI, regulations and Standards do not provide any ranges or tables, thus the final score is computed using the Equation6.1. Even if DGI can range from 0 to 28, the limit threshold is set at 22, that corresponds to the point at which people experience discomfort. In Table6.9 are reported the maximum and minimum limit values for this index.

The overall score for this part is computed as an arithmetic mean between the scores reached by each Key Performance Indicator.

KPI	$val_{limit,min}$	$val_{limit,max}$
Unified Glare Rating (UGR)	22	0

Table 6.9: Maximum and minimum limit values for Daylight Glare Index for the score normalization procedure.

6.1.3. Long-term assessment

The Long-term assessment has been proposed with the aim of evaluating the Smart Readiness Indicator at the end of a representative period, such as a season, a month or a year, using data recorded every pre-defined time-step (e.g. every hour). In this case, the SRI assumes values that correspond to the average performance level maintained during the considered assessment period. This can be done considering the effective indoor conditions through the use of the proposed long-term KPIs. Table6.10 gives an overview of all the indices proposed for this SRI assessment.

Long-Term KPIs

KPI	SRI associated domain	SRI associated Impact Criteria	Reference
Severity of Dis-compliance (SD)	Heating, Cooling, Controlled ventilation	Comfort	G. Vergerio, C. Becchio[45]
Percentage Outside Range (POR)	Heating, Cooling, Controlled ventilation	Health	CEN/TR 16798-2:2019[72]
Daylight Factor (DF)	Dynamic Envelope	Comfort	EN 17037:2018[69]
Daylight Glare Index (DGI)	Dynamic Envelope	Health	Carlucci et al.[29]

Table 6.10: Key Performance Indicators for the SRI long-term assessment.

Severity of Dis-compliance (DS) for Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)

For the long-term assessment of impacts on "Comfort" for services belonging to Heating and Cooling domains, the KPI chosen is the Severity of Dis-compliance for both PMV and PPD. According to Ref.[45], the score for the Fanger's indices is computed as the average between the hourly-score reached by the SD for the two metrics for the entire considered period. The hourly-score is evaluated using Table6.14, in which for every class is defined the severity degree and the associated color code and score.

The overall score is computed as the average between the score reached by SD-PMV

PMV range	PPD range	SD	Score
$-0.2 \leq \text{PMV} \leq 0.2$	$< 6\,\%$	0	3
$-0.5 \leq \text{PMV} \leq 0.5$	$< 10\,\%$	1	2
$-0.7 \leq \text{PMV} \leq 0.7$	$< 15\,\%$	2	1
$> 0.7 \wedge \text{PMV} < -0.7$	$> 15\,\%$	3	0

Table 6.11: Scoring table for Severity of Dis-compliance (SD) index for PMV and PPD. Data are from[71] and [45].

index and the one reached by the SD-PPD index.

Percentage Outside Range (POR) for operative temperature

To evaluate long-term impacts on "Health and Well-being" for services under the Heating and Cooling domains, the chosen KPI is the Percentage of time Outside Range (POR) for the operative temperature.

The ranges to evaluate the final score are given by the CEN/TR 16798-2:2019[72] and for each of them is proposed a rating that reflects the performance level implemented in the interior space. The ranges define the percentage of time for week, month and year as a maximum amount of occupied hours in which the considered index exceeds the limit threshold.

Operative temperature range	
Heating season	Cooling season
$22 \pm 3\,°\text{C}$	$24.5 \pm 2.5\,°\text{C}$

Table 6.12: Reference operative temperature ranges for the POR calculation. Data are from[71].

Weekly POR	Monthly POR	Yearly POR	Score
$0\,\%$	$0\,\%$	$0\,\%$	3
$< 20\,\%$	$< 12\,\%$	$< 3\,\%$	2
$20\,\% < \text{POR} < 50\,\%$	$12\,\% < \text{POR} < 25\,\%$	$3\,\% < \text{POR} < 6\,\%$	1
$> 50\,\%$	$> 25\,\%$	$> 6\,\%$	0

Table 6.13: Scoring table for Percentage Outside Range (POR) index for Operative temperature. Data are from[68].

Severity of Dis-compliance (DS) for air speed

As stated for PMV and PPD indices, the long-term assessment of impacts on "Comfort" for services belonging to Controlled ventilation domain is carried out using the Severity of Dis-compliance for air speed. According to Ref.[45], the score for this index is computed as the average of all the hourly-score reached by the SD during the entire assessment period. The hourly-score is evaluated using Table6.14, in which for every class is defined the severity degree and the associated color code and score.

Heating season			Cooling season		
Air speed range	SD	Score	Air speed range	SD	Score
$< 0.10\,\mathrm{m/s}$	0	3	$< 0.12\,\mathrm{m/s}$	0	3
$0.10\,\mathrm{m/s} < v < 0.16\,\mathrm{m/s}$	1	2	$0.12\,\mathrm{m/s} < v < 0.19\,\mathrm{m/s}$	1	2
$0.16\,\mathrm{m/s} < v < 0.21\,\mathrm{m/s}$	2	1	$0.19\,\mathrm{m/s} < v < 0.24\,\mathrm{m/s}$	2	1
$> 0.21\,\mathrm{m/s}$	3	0	$> 0.24\,\mathrm{m/s}$	3	0

Table 6.14: Scoring table for Severity of Dis-compliance (SD) index for PMV and PPD. Data are from[71] and [45].

Percentage Outside Range for CO_2 concentration

To assess impacts on "Health and Well-being" for services under the Controlled ventilation domain, the chosen KPI is the Percentage of time Outside Range (POR) for the CO_2 concentration in the indoor space.

Also in this case, the ranges to evaluate the final score are given by the CEN/TR 16798-2:2019[72] and for each of them is proposed a rating that reflects the performance level implemented in the interior space. The ranges define the percentage of time for week, month and year as a maximum amount of occupied hours in which the considered index exceeds the limit threshold, as showed in Table6.15.

$CO_2 > 1350\,\mathrm{ppm}$			
Weekly POR	Monthly POR	Yearly POR	Score
$0\,\%$	$0\,\%$	$0\,\%$	3
$< 20\,\%$	$< 12\,\%$	$< 3\,\%$	2
$20\,\% <$ POR$50\,\%$	$12\,\% <$ POR $< 25\,\%$	$3\,\% <$ POR $< 6\,\%$	1
$> 50\,\%$	$> 25\,\%$	$> 6\,\%$	0

Table 6.15: Scoring table for Percentage Outside Range (POR) index for CO_2 concentration KPI. Data are from[68].

Daylight Factor (DF)

To evaluate the long-term impacts on "Comfort" concerning services under the "Dynamic envelope" domain, it has been decided to use the Daylight Factor (DF) during the defined time-period.

According to EN 17037:2018, the Daylight Factor has to reach the Daylight target (DT) for a minimum of $50\,\%$ of the occupied time. Starting from this assumption, the scoring method proposed is based on the normalization, between 0 and 3, of the percentage of time during which the DF is greater than the DT. For this purpose, in Table6.16 are reported the minimum and the maximum value and the associated score for the long-term evaluation of the Daylight Factor. This ranges are computed using value provided by the standards for Italian locations.

DF $> 1.6\,\%$	Score
$100\,\%$	3
$< 50\,\%$	0

Table 6.16: Scoring table for the long-term evaluation of Daylight Factor (DF). Data are from[69].

Percentage Outside Range (POR) for Daylight Glare Index (DGI)

To assess impacts on "Health and Well-being" for services under the Dynamic envelope domain, the chosen KPI is the Percentage (of time) Outside Range (POR) concerning the Daylight Glare Index (DGI) in the indoor space.

As stated before, the ranges to evaluate the final score are given by the CEN/TR 16798-2:2019[72] and for each of them is proposed a rating that reflects the performance level implemented in the interior space. The ranges define the percentage of time for week, month and year as a maximum amount of occupied hours in which the considered index exceeds the limit threshold, as showed in Table6.17.

DGI> 22			
Weekly POR	Monthly POR	Yearly POR	Score
$0\,\%$	$0\,\%$	$0\,\%$	3
$< 20\,\%$	$< 12\,\%$	$< 3\,\%$	2
$20\,\% <$ POR$50\,\%$	$12\,\% <$ POR $< 25\,\%$	$3\,\% <$ POR $< 6\,\%$	1
$> 50\,\%$	$> 25\,\%$	$> 6\,\%$	0

Table 6.17: Scoring table for Percentage Outside Range (POR) index for Daylight Glare Index.

6.2. Determination of new weighting factors for SRI methodology using the Analytic Hierarchy Process

The actual SRI methodological framework is structured to give the same importance to Impact Criteria and technical Domains under each of them for the ones belonging to the ones belonging to the Key Functionality "Respond to users' needs".

In this Chapter a Multi-Criteria Decision-Making method is chosen and developed aiming to compute new weighting factors for the SRI that can represent the real importance of Domains and Impact Criteria for defined European locations and building types.

This procedure is intended to obtain results for building located in Italy, in order to give an effective contribution for future developments of the Smart Readiness Indicator.

6.2.1. Definition of a top-down structure for the SRI

The first step in determining weighting factors using the Analytic Hierarchy Process is to start structuring top down, intended as the organization of the entire work into a hierarchical structure composed by an overall goal on the top followed by different levels and sub-levels that identify criteria and alternatives. In this work the main objective is to find new weights for the categories "Comfort", "Convenience", Health & Well-being" and "Information to Occupants", that are currently equal weighted.

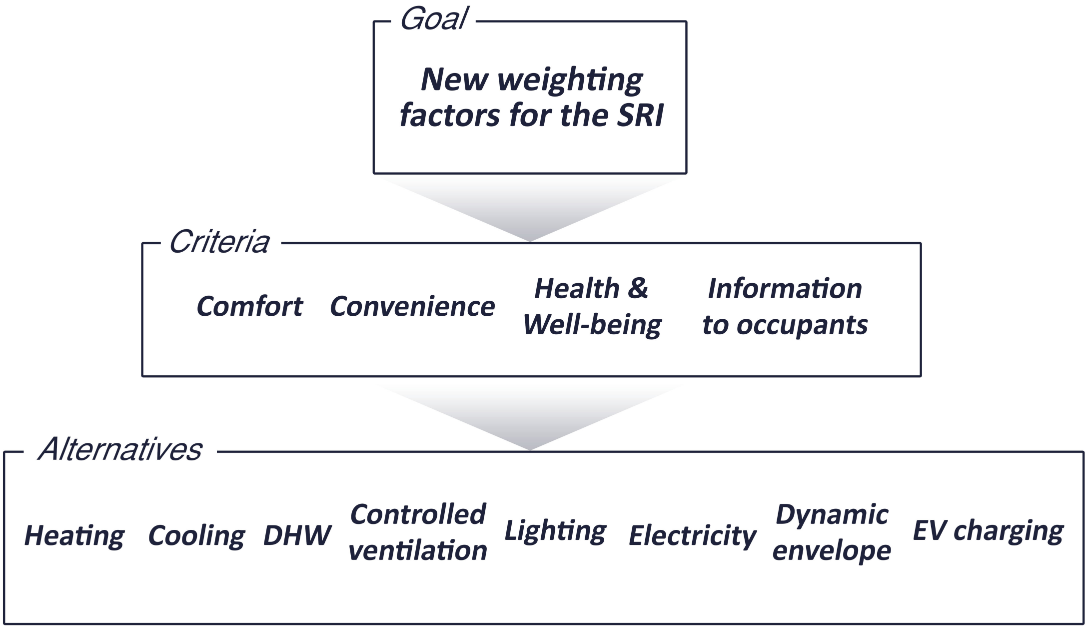


Figure 6.2: Top-down structure implemented for the determination of new weighting factors in the Smart Readiness Indicator methodology.

Consequently, as showed in Fig.6.2, the first level is made up of four main criteria, represented by the aforementioned categories of the Smart Readiness Indicator, whereas the alternatives sub-level is composed by the nine domains presented in the European rating scheme methodology.

6.2.2. Construction of the questionnaire and data collection

The method proposed by Saaty[63] requires the a process of data collection from questionnaire, in which the subjects involved can express their priorities with respect to a set of proposed question regarding a particular focus. In this case, the top-down structures identify two different levels of criteria and alternatives for which two different type of question shall be developed. Indeed, the proposed questionnaire, concerning the non-residential building type, is divided in two main parts: the first one is intended to derive a comparison matrix for the alternatives, i.e. the four impact criteria under the key capability "Respond to users' need", while the second aims to compute the comparisons matrices regarding the nine domains of the Smart Readiness Indicator methodology.

Therefore, in the first level the impact criteria related to "Respond to users' need" are compared one to each other, using the AHP typical sentence's formulation. Indeed, a typical question could be "Between *Impact Criteria 1* and *Impact Criteria 2* how much one is important over the other?", as showed in Fig.6.3.

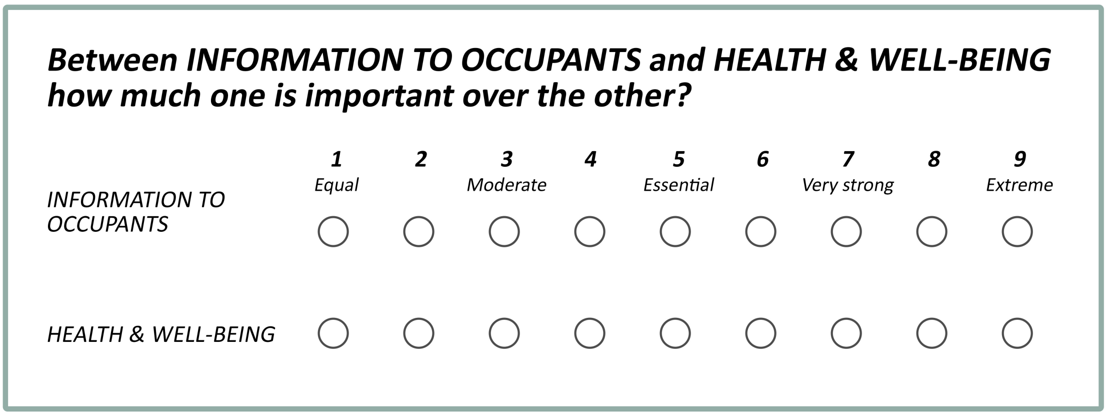


Figure 6.3: Example of question proposed in the first part of the questionnaire developed for the application of the AHP method.

Consequently, the proposed question requires to express a preference between two main criteria using the fundamental scale of the AHP[63]. For each question two lines related to the degree of importance of one parameter with respect to the other one are given and the decision maker can choose the line corresponding to the most important parameter in its opinion selecting a score from 1 to 9. For each question only one answer on the chosen line can be given.

Moreover, in order to avoid incomprehension and to simplify the survey, for each part a briefly description of the main terms is provided, together with guidelines for answering in the correct way.

The second part of the questionnaire is composed by similar question, but in this case the choice has to be made between two domains with respect to one of the four Impact Criteria. Therefore, the typical question proposed is "For what concerns *Impact Criteria 1*, what is more important between *Domain 1* and *Domain 2*?", as showed in Fig.6.4.

The questionnaire is carried out by a group of ten experts in this research field with a background in Architecture and Engineering, in order to collect consistent data and to obtain results able to better represent the preferences for non-residential building.

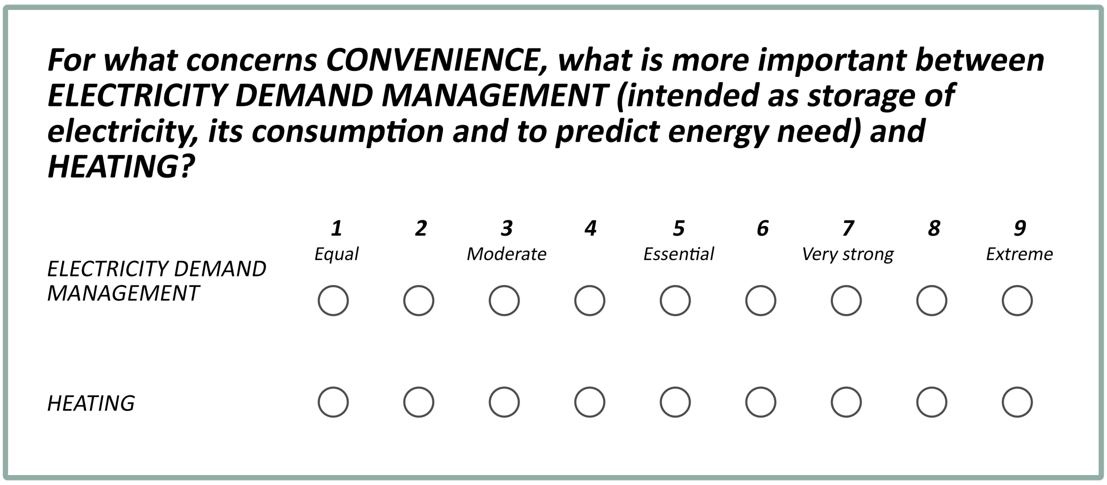


Figure 6.4: Example of question proposed in the second part of the questionnaire developed for the application of the AHP method.

6.2.3. The comparison matrices

Every questionnaire has produced two matrices as result: the first one is a square matrix in which are reported the judgments related to the degree of importance of an Impact Criteria with respect to the other ones under the Key Functionality "Respond to users' needs". The other square matrix deriving from the second part of the questionnaire, reports judgments about the importance level reached by each domain compared to others with respect to every Impact Criteria analyzed before.

Therefore, all the judgment matrices related to the first part and all the matrices related to the second section are synthesized using the geometric mean, obtaining a single matrix related impact criteria (first part) and four matrices related to domains under a specific impact criteria (second part). The geometric mean is computed as the n^{th} root product of the values as follows:

$$GM = \sqrt[n]{x_1 \cdot x_2 \cdot \ldots \cdot x_n} \tag{6.2}$$

The final matrices obtained from questionnaire are reported below in order to make more comprehensible the entire procedure.

6.2.4. The final weighting factors

The final weighting factors are computed using the Principal Eigenvalue method developed by Saaty[63]. Starting from the Impact Criteria matrix obtained from the aggregation using the geometric mean (see Fig.6.5), the eigenvector associated to the maximum eigenvalue of this matrix is calculated. With the aim to improve the entire procedure, reduce errors and avoid time waste, all these passages were done using the software called Python. Such a matrix is checked for consistency problems and its Consistency Index results equal to 0.067, thus no correction is applied to data.

	Comfort	Convenience	Health & Well-being	Information to occupants
Comfort	1.00	3.00	0.50	4.00
Convenience	0.33	1.00	0.33	0.50
Health & Well-being	2.00	3.00	1.00	4.00
Information to occupants	0.25	2.00	0.25	1.00

Figure 6.5: Matrix of Impact Criteria obtained from data aggregation using the geometric mean.

COMFORT	Heating	Cooling	Controlled ventilation	DHW	Lighting	Electricity	Dynamic envelope	EV charging
Heating	1.00	1.00	3.00	0.00	2.00	0.00	5.00	0.00
Cooling	1.00	1.00	2.00	0.00	2.00	0.00	2.00	0.00
Controlled ventilation	0.33	0.50	1.00	0.00	2.00	0.00	4.00	0.00
DHW	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lighting	0.50	0.50	0.50	0.00	1.00	0.00	2.00	0.00
Electricity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dynamic envelope	0.20	0.50	0.25	0.00	0.50	0.00	1.00	0.00
EV charging	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

HEALTH & WELL-BEING	Heating	Cooling	Controlled ventilation	DHW	Lighting	Electricity	Dynamic envelope	EV charging
Heating	1.00	2.00	1.00	0.00	2.00	0.00	4.00	0.00
Cooling	0.50	1.00	0.50	0.00	1.00	0.00	2.00	0.00
Controlled ventilation	1.00	2.00	1.00	0.00	3.00	0.00	6.00	0.00
DHW	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lighting	0.50	1.00	0.33	0.00	1.00	0.00	3.00	0.00
Electricity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dynamic envelope	0.25	0.50	0.17	0.00	0.33	0.00	1.00	0.00
EV charging	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 6.6: Matrices obtained from data aggregation using the geometric mean.

Therefore, the computed eigenvector provides the set of priorities, i.e. weighting factors, associated to the Impact Criteria "Comfort", "Health and Well-being", "Convenience" and "Information to occupants". The new weighting factors, as showed in Fig.6.8, are quite similar to the ones given by the SRI methodology (i.e. 0.08 for all of them), but they

COMFORT	Heating	Cooling	Controlled ventilation	DHW	Lighting	Electricity	Dynamic envelope	EV charging
Heating	1.00	1.00	3.00	0.00	2.00	0.00	5.00	0.00
Cooling	1.00	1.00	2.00	0.00	2.00	0.00	2.00	0.00
Controlled ventilation	0.33	0.50	1.00	0.00	2.00	0.00	4.00	0.00
DHW	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lighting	0.50	0.50	0.50	0.00	1.00	0.00	2.00	0.00
Electricity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dynamic envelope	0.20	0.50	0.25	0.00	0.50	0.00	1.00	0.00
EV charging	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

HEALTH & WELL-BEING	Heating	Cooling	Controlled ventilation	DHW	Lighting	Electricity	Dynamic envelope	EV charging
Heating	1.00	2.00	1.00	0.00	2.00	0.00	4.00	0.00
Cooling	0.50	1.00	0.50	0.00	1.00	0.00	2.00	0.00
Controlled ventilation	1.00	2.00	1.00	0.00	3.00	0.00	6.00	0.00
DHW	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lighting	0.50	1.00	0.33	0.00	1.00	0.00	3.00	0.00
Electricity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dynamic envelope	0.25	0.50	0.17	0.00	0.33	0.00	1.00	0.00
EV charging	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 6.7: Matrices obtained from data aggregation using the geometric mean.

better reflects the degree of importance of certain criteria with respect to others.

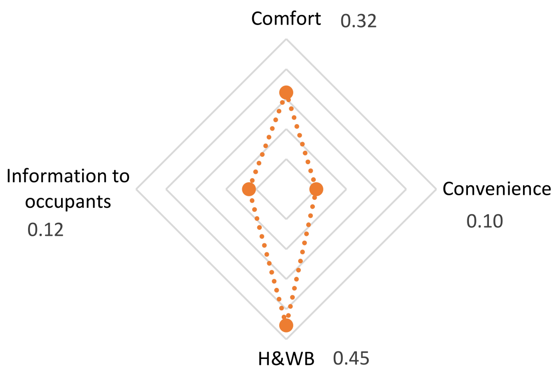


Figure 6.8: New weighting factors for Impact Criteria in the SRI methodology.

Consequently, at the domain level, the same procedure is carried out for the four matrices containing data related to the domains comparisons under each of the aforementioned criteria.

Also for these matrices the data consistency is checked, obtaining the following Consistency Indices: for the domains' matrix related to "Comfort" the CI is equal to 0.054, for the domains' matrix under "Convenience" criteria the CI is equal to 0.029, for the domains' matrix belonging to "Health and Well-being the consistency index is 0.010 and finally, for the domains' matrix associated to "Information to occupants" criteria the CI is equal to 0.042. All these Consistency Index are less than the fixed threshold of 10 %, therefore, data does not require any adjustment.

For each matrix is computed the eigenvector associated to the maximum eigenvalue, obtaining all the weights vectors applicable to domains.

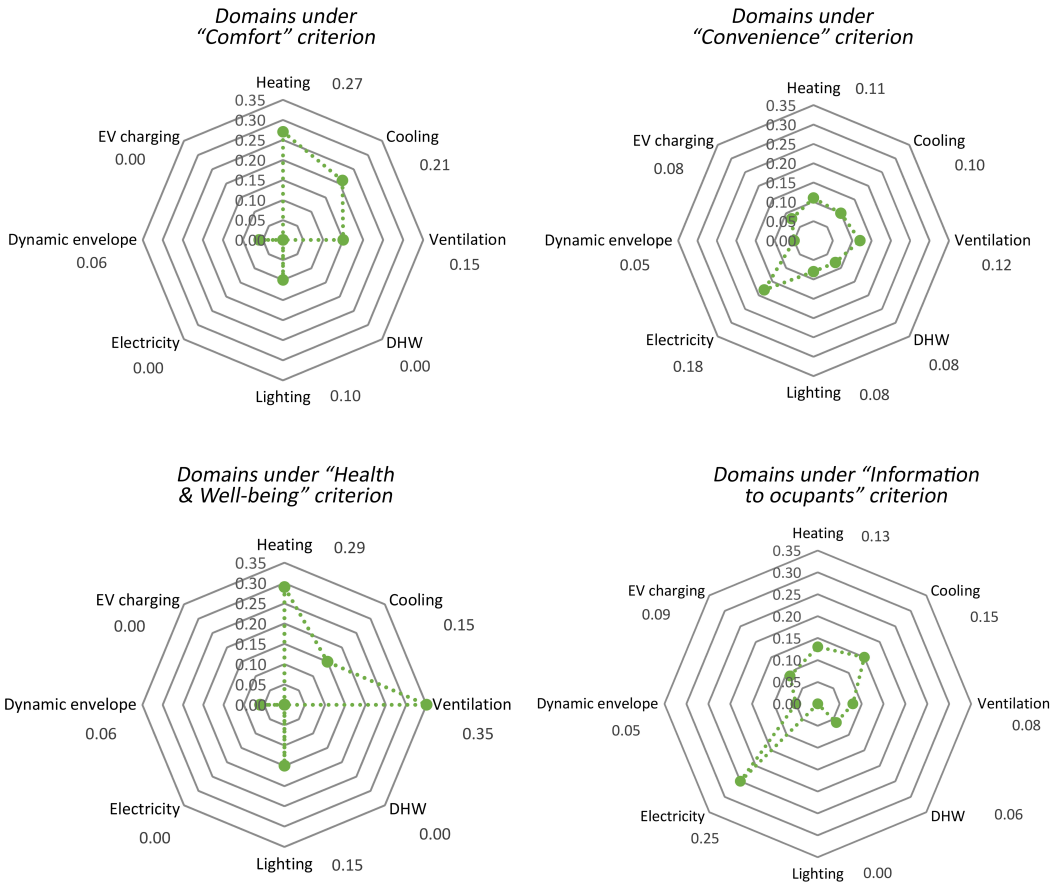
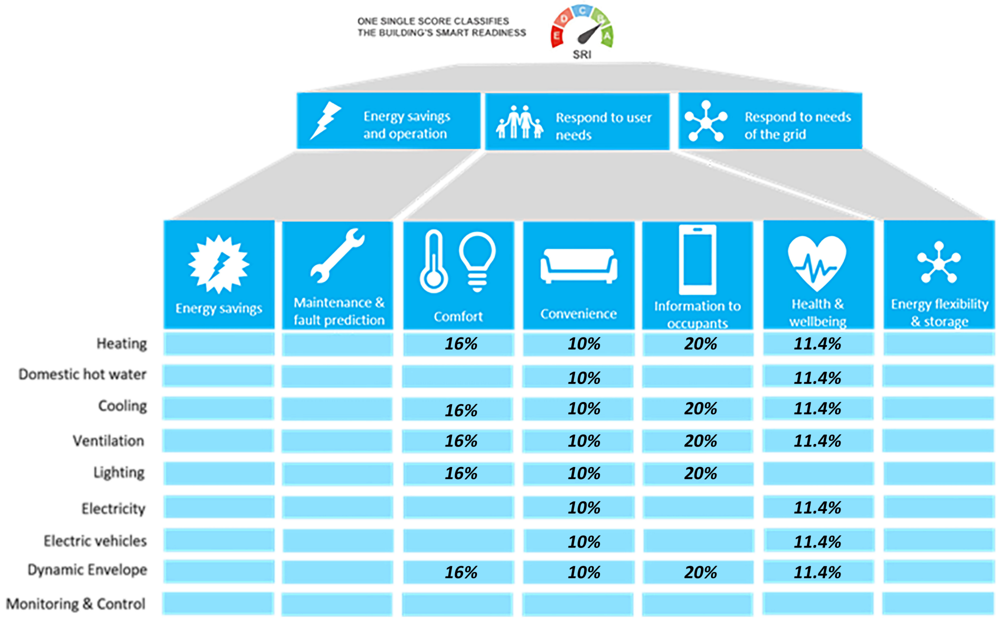


Figure 6.9: New weighting factors for the technical Domains under each Impact Criterion in the SRI methodology.

Also at the domains level, the new weighting factors, as showed in Fig.6.9, are quite similar to the ones given by the SRI methodology (i.e. 16 % for domains under "Comfort", 20 % "Health and Well-being", 10 % for domains under "Convenience" and 11.4 % for domains under "Information to occupants"), but they better reflects the impacts that certain domains have on a defined Impact Criterion with respect to the others. A comparison between the weighting factors currently used by the SRI methodology and the new ones proposed in this work is showed in Fig.6.10.

Current SRI weighting factors



New SRI weighting factors

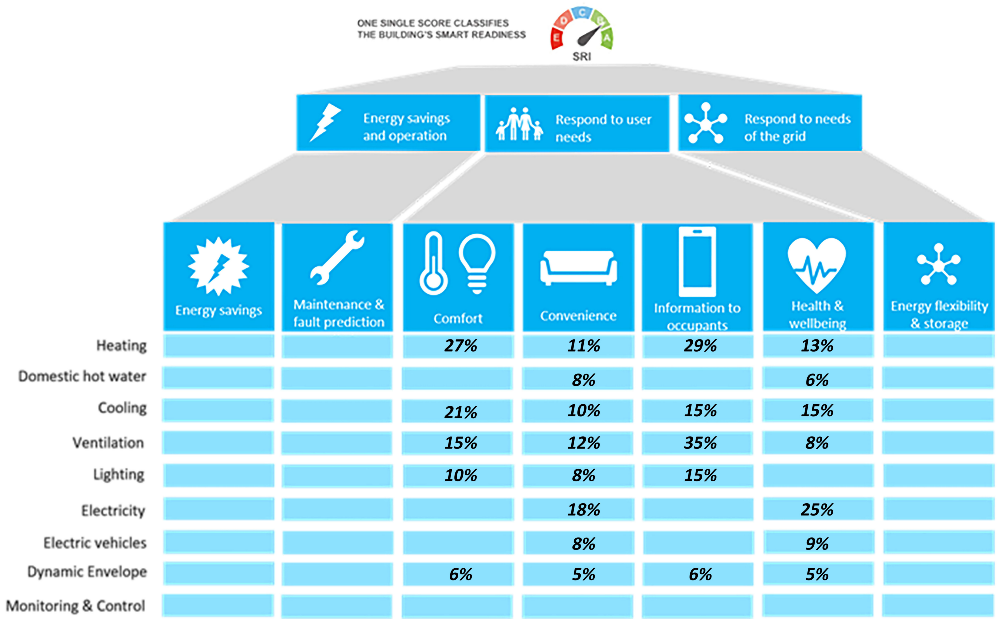


Figure 6.10: Comparison between the weights currently defined by the SRI's Final Report (above) and the proposed new one computed with AHP method (below).

7. Case study

In this Chapter is presented a case study in order to better explain the thesis work developed in the previous section. In the first part a description of the test building is provided, giving information about how it is structured and oriented, aiming to give an idea of the space configuration.

Afterwards, the analysis of the main Key Performance Indicator presented in Chapter 4 is carried out in order to give a score for each smart service that has impact on the SRI criteria "Comfort" and "Health and Well-being". Moreover, for this case study is also computed the final SRI score, involving the use of the new weighting factors generated from the Analytic Hierarchy Process in the related chapter.

7.1. Description of the building

The test facility analyzed in this thesis work consists of an office located within a building which is structured in two office rooms, one control room and a technical space. The considered office has a rectangular layout, with a floor area equal to $32.85\,\mathrm{m}^2$ ($6.55 \times 5.02\,\mathrm{m}$) and two openings, the smaller one ($0.73 \times 2.30\,\mathrm{m}$) in correspondence of the north-west side and the other ($2.60 \times 2.30\,\mathrm{m}$) facing south-east, as showed in Fig.7.1.

According to the sections proposed in Fig.7.2 and Fig.7.3, the ceiling height ranges between 2.84 m or 2.94 m at the minimum and 3.71 m at the maximum above the floor level, due to the slope differences of the roof, respectively 13.4° on south-east side and 15° on north-west side.

The office space is designed to contain up to ten occupants that work inside for a maximum of ten hours during the day, for the entire week excluding Saturday and Sunday.

7.2. Implementation of the proposed new methodology for the Smart Readiness Indicator

With a view to implement the new methodology proposed in the previous chapter, the first step required the acquisition of data related to the office's space using a software called EnergyPlus™. It is an open source software useful to carry out energy simulation to the whole building and used by engineers, architects and researchers to model energy consumption for heating, cooling, ventilation, lighting and plug and process loads, together with water use in buildings[43].

The entire analysis has been set during the cooling season, in June, with a sampling time-step of an hour during which the software has provided indicator or useful variables

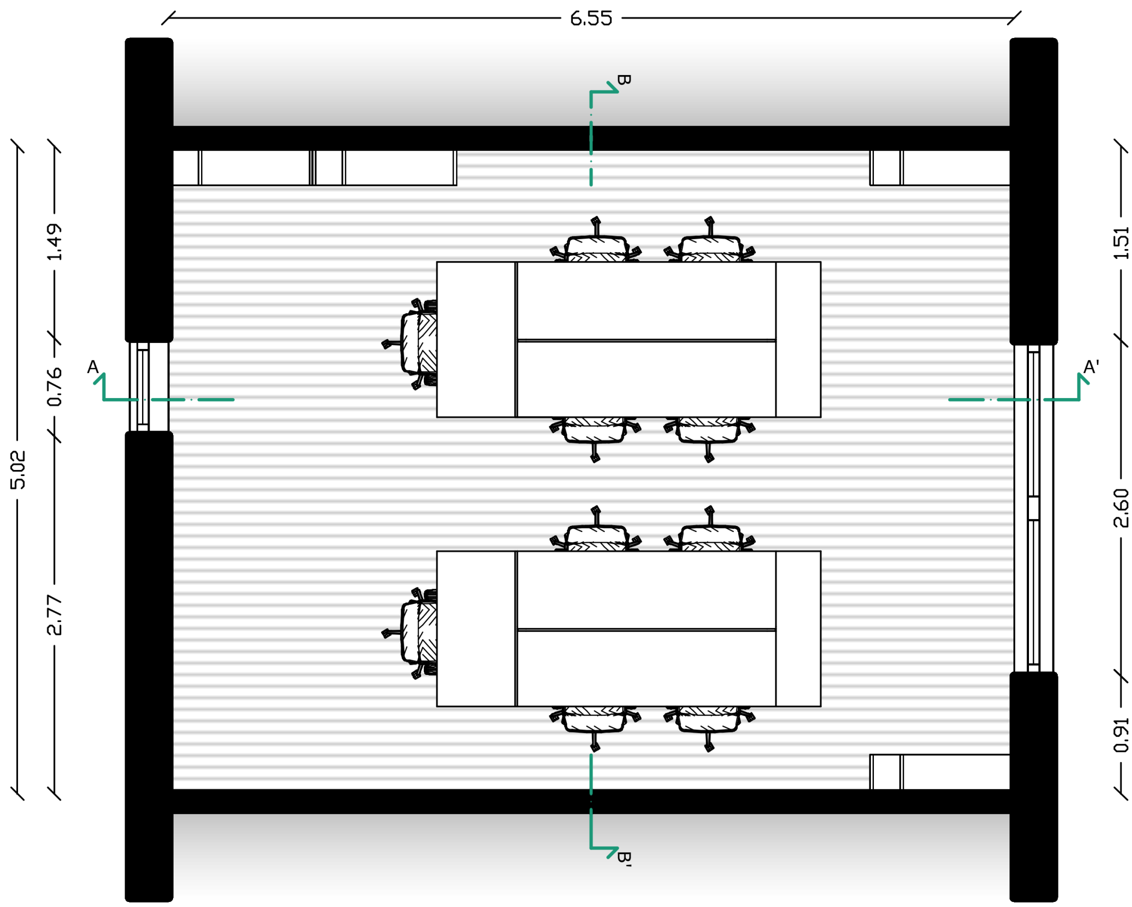


Figure 7.1: Office's floor plan. Out of scale.

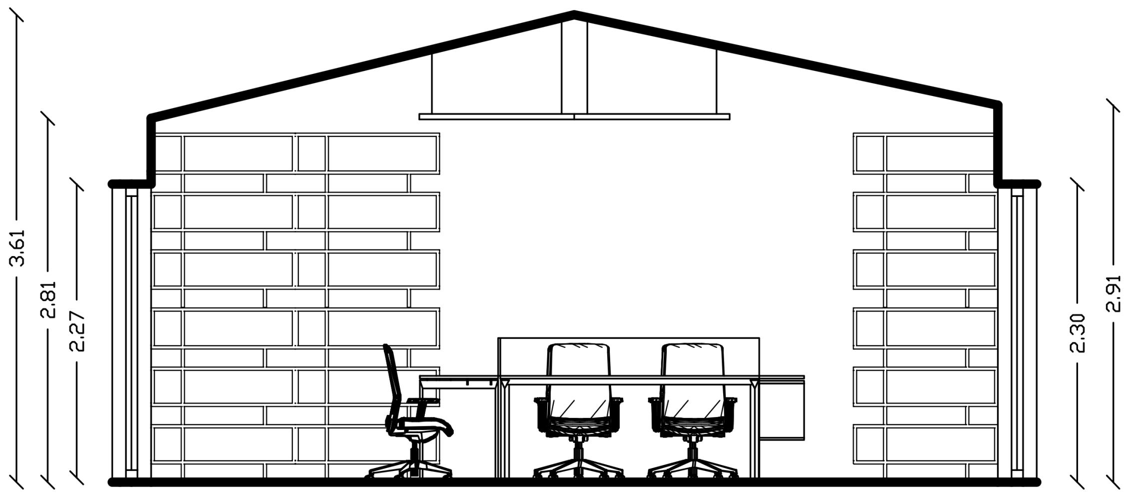


Figure 7.2: Section AA'. Out of scale.

for their calculation as output. In particular, the output data include the Fanger's Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), the mean air temperature, the air speed, the daylight illuminance on the reference workplane and value

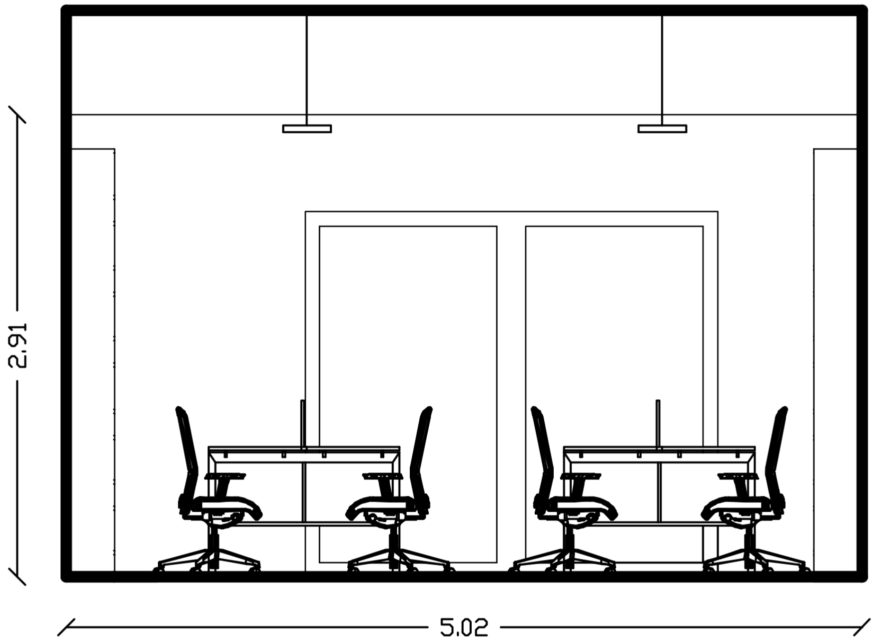


Figure 7.3: Section BB'. Out of scale.

regarding the assessment of glare in the interior space due to daylight, i.e. the Daylight Glare Index values.

It should be specified that all the variables and indices derived from EnergyPlus™were analyzed only for the time period in which a sensor has detected the occupants' presence, i.e. during the working hours from 9.00 a.m to 6.00 p.m., from Monday to Friday. This is due to the fact that the entire system was designed to maintain the specified indoor climate conditions only when the occupancy level is different from zero, aiming to save energy during the unoccupied time-span.

7.2.1. Steady-state evaluation

The steady-state analysis about the selected Key Performance Indicator for the computation of scores about Comfort and Health and Well-being levels was carried out on June 21st. For each working hour of the day KPIs are evaluated in order to compute a final SRI score for every considered hour.

In the following paragraphs will be analyzed all the indices mentioned in Chapter 6, specifying the computation methodology and their score's definition, according to the procedure stated in the aforementioned chapter.

Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)

The Fanger's Indices Predicted Mean Vote and Predicted Percentage of Dissatisfied (PPD) are the two KPIs chosen to assess the impact on "Comfort" for Heating/Cooling domain's services in the SRI methodology. They were directly generated from EnergyPlus™.

Class	Range	Score
I	$-0.2 \leq \text{PMV} \leq 0.2$	3
II	$-0.5 \leq \text{PMV} \leq 0.5$	2
III	$-0.7 \leq \text{PMV} \leq 0.7$	1
IV	$\text{PMV} > 0.7 \wedge \text{PMV} < -0.7$	0
Class	**Range**	**Score**
I	$\text{PPD} \leq 6\,\%$	3
II	$\text{PPD} \leq 10\,\%$	2
III	$\text{PPD} \leq 15\,\%$	1
IV	$\text{PPD} > 15\,\%$	0

Table 7.1: Threshold values for assessing the score of Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). Data are from[68].

The associated score are computed using ranges specified in Chapter 6 and also defined by Standards EN 16798-1:2019 and ISO 7730:2005. For instance, the scores obtained at 12.00 p.m. are respectively 0 for the PMV, which belongs to class IV, and also 0 for the PPD belonging to class IV (see Table7.1). Therefore, the overall score, obtained as an arithmetic mean between the two scores, is zero.

Air temperature

To assess the impact on "Health and Well-being" for Heating and Cooling services the chosen Key Performance Indicator is the Air Temperature. This metric is directly generated from the software. For instance, at 12 p.m., according to ranges defined in Chapter 6 using data from EN 16798-1:2019 and ISO 7730:2005, the score reached by this KPI is 2, because of it belongs to category B.

Class	Range	Score
A	$24.5 \pm 1.0\,^{\circ}\text{C}$	3
B	$24.5 \pm 1.0\,^{\circ}\text{C}$	2
C	$24.5 \pm 1.0\,^{\circ}\text{C}$	1
-	$T > 27\,^{\circ}\text{C} \wedge T < 22\,^{\circ}\text{C}$	0

Table 7.2: Threshold values for assessing the score related to the Air Temperature metric. Data are from[71].

Air speed

In this case study the air speed is set at $0.137\ \text{m/s}$ and it remains constant for the entire time period in which the analysis is carried out. Therefore, the score achieved for "Comfort" in

Controlled Ventilation services is 2 for all the working hours, due to the fact that the KPI value belongs to class II, as showed below in Table7.3.

Class	Range	Score
A	$\leq 0.12\,\mathrm{m/s}$	3
B	$\leq 0.19\,\mathrm{m/s}$	2
C	$\leq 0.24\,\mathrm{m/s}$	1
-	$> 0.24\,\mathrm{m/s}$	0

Table 7.3: Threshold values for assessing the score related to the Air speed. Data are from[71].

CO_2 concentration

To assess the impact on "Health and Well-being" for Controlled ventilation services the chosen index is the CO_2 concentration, even if will be an estimated value rather than an output of EnergyPlus™. According to EN 16798-1:2019[68], the CO_2 emission rate is assumed to be about 20 L/(h per person). Therefore, the total pollutant concentration above the outdoor concentration considering the office as fully occupied, i.e. all the ten users are present, is about 1032.05 ppm. Consequently, being that this metric belongs to class III, the score achieved is 1 for the entire occupied period.

Class	Range	Score
I	$\leq 550\,\mathrm{ppm}$	3
II	$\leq 800\,\mathrm{ppm}$	2
III	$\leq 1350\,\mathrm{ppm}$	1
IV	$> 1350\,\mathrm{ppm}$	0

Table 7.4: Threshold values for assessing the score related to the CO_2 levels in indoor spaces. Data are from[68].

Unified Glare Rating (UGR), Visual Comfort Probability (VCP) and Color Rendering Index (CRI)

For what concerns artificial light, the office space presents four LED lighting fixtures DURALamp type "SLIMFLUX VINTAGE 30X120 - PLUS" of 33 W, placed centrally in the room. The chosen KPIs for the evaluation of "Comfort" criterion in Lighting services are the Unified Glare Rating (UGR), the Visual Comfort Probability (VCP) and the Color Rendering Index (CRI).

According to technical specification, the Color Rendering Index is greater than 80, then the score achieved is 1, according to what explained in Chapter 6.

Consequently, the UGR value, computed choosing the worst value between all the UGR values reached in different points of view of the users, is about 18.95. Therefore, the score obtained, normalized between the UGR range (16-19), is 0.

The Visual Comfort Probability, computed using the relation between UGR and VCP explained by R.G. Mistrick et al. in Ref.[59], is about 62 %, thus the score is normalized in the VCP range explained in the previous chapter, with a final result of 0. The final score is computed as an arithmetic mean of the three scores reached by the aforementioned indices, and it is equal to zero for all the occupied hours.

Equivalent Melanopic Lux (EML)

To assess the impact on "Health and Well-being" for Lighting services the chosen index is the Equivalent Melanopic Lux, evaluated using the equation presented in Chapter 4. With a vertical illuminance (E_v) of 528.30 lux, measured on a vertical plane at the height of 1.20 m from the floor, and a melanopic ratio (R) of 0.76, computed using the tool provided by WELLv2 certification[53], the EML is 401.5 lux. The final score, obtained normalizing the EML as stated in Chapter 6, is equal to 3 for the entire day.

Dayight Factor (DF)

The impact on "Comfort" for the Dynamic Envelope services is evaluated using the Daylight Factor. The EnergyPlus software gives the illuminance level at a reference workplane located at 0.83 m abve the floor. The workplane considered corresponds to two desks placed in the centre of the office space and for the calculation it is divided in six points using a grid of 0.60 × 0.87 meters, as showed in Fig.7.4. In each point is then computed the Daylight Factor and the final value is obtained as an average value of all the twelve DF values calculated.

Daylight Glare Index (DGI) and Daylight Glare Probability (DGP)

For the "health and Well-being" impact criterion in the Dynamic Envelope domain, the score for the services are computed using the Daylight Glare Index (DGI) and the Daylight Glare Probability (DGP). All these value are computed for the entire working period. For instance, for what concerns the DGI at 12.00 p.m., the output from EnergyPlus gives a value of 17.32, which is related to a score of 1 point. On the other hand, the Daylight Glare Probability assessed at the same time is equal to 0.23, thus the final score assigned is 3 according to the ranges defined in Chapter 6.

The final scores from Key Performance Indicator

As explained in chapter 6, the new proposed methodology computes the ultimate service's score for each Impact Criteria as an average between the score given by the SRI methodology due to the level of functionality implemented in the building, and the score resulting from the KPIs assessment.

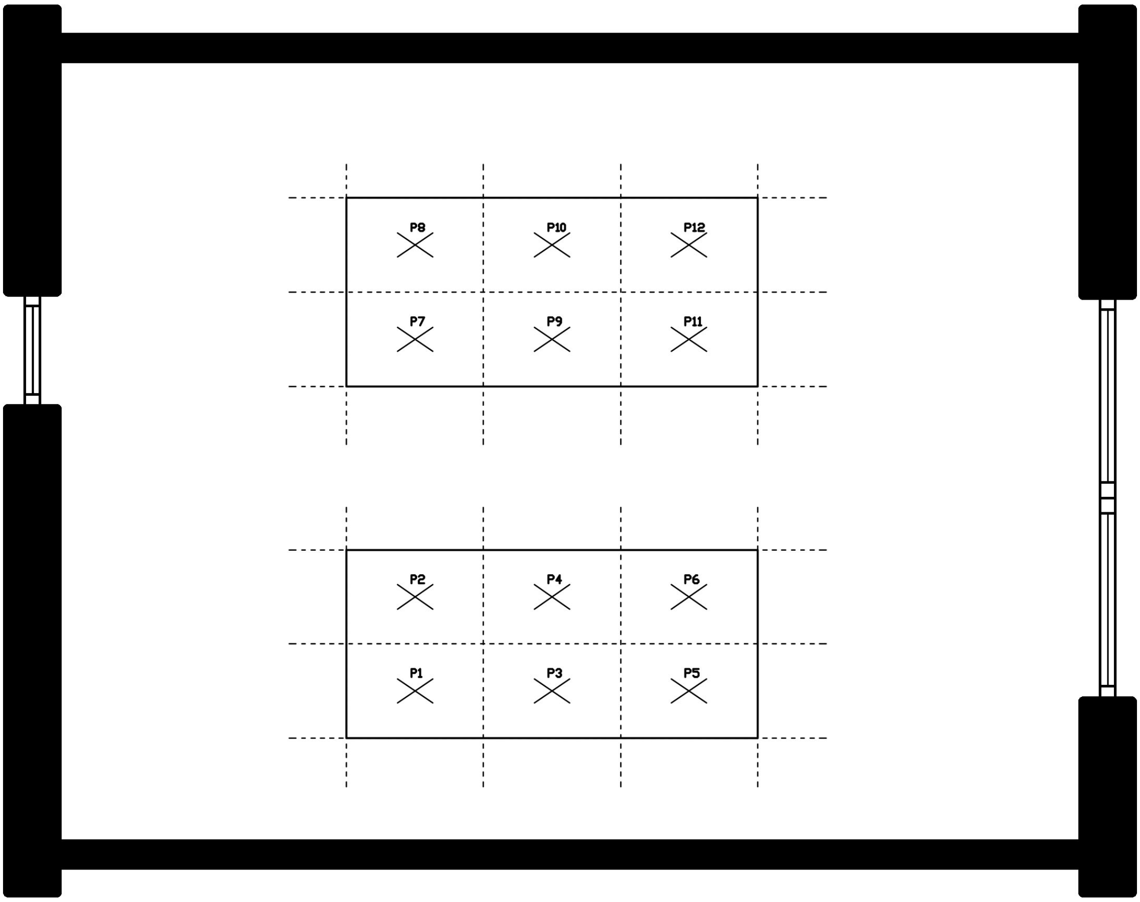


Figure 7.4: Office's floor plan with a representation of the grid used for the computation of Daylight Factor (DF). Out of scale.

This procedure is done for the entire occupied time-period, computing the service's scores every hour. Consequently, the overall scores have changed every time in which the indoor conditions have changed too.

7.2.2. Long-term assessment

The Long-term assessment about the selected Key Performance Indicator for the computation of scores about Comfort and Health and Well-being levels was carried out considering all the working hours in June, i.e. from 9.00 a.m. to 6.00 p.m. from Monday to Friday, amounting to 220 hours.

In the following paragraphs will be analyzed all the indices mentioned in Chapter 6, specifying the computation methodology and their score's definition, according to the procedure stated in the aforementioned chapter.

Severity of Dis-compliance (SD) for PMV and PPD indices

For the evaluation of the impact on "Comfort" in services under the Cooling domain was used the Severity of Dis-compliance index. It is evaluated both for Predicted Mean Vote

(PMV) and Predicted Percentage of Dissatisfied (PPD) and the final SD value is computed as an arithmetic mean between the SD index of each KPI. Therefore, according to what stated in Chapter 6 and the figure showed below (Fig.7.5), the final score assigned for this index is 1, due to the fact that the average SD value between PMV and PPD belongs to Class III.

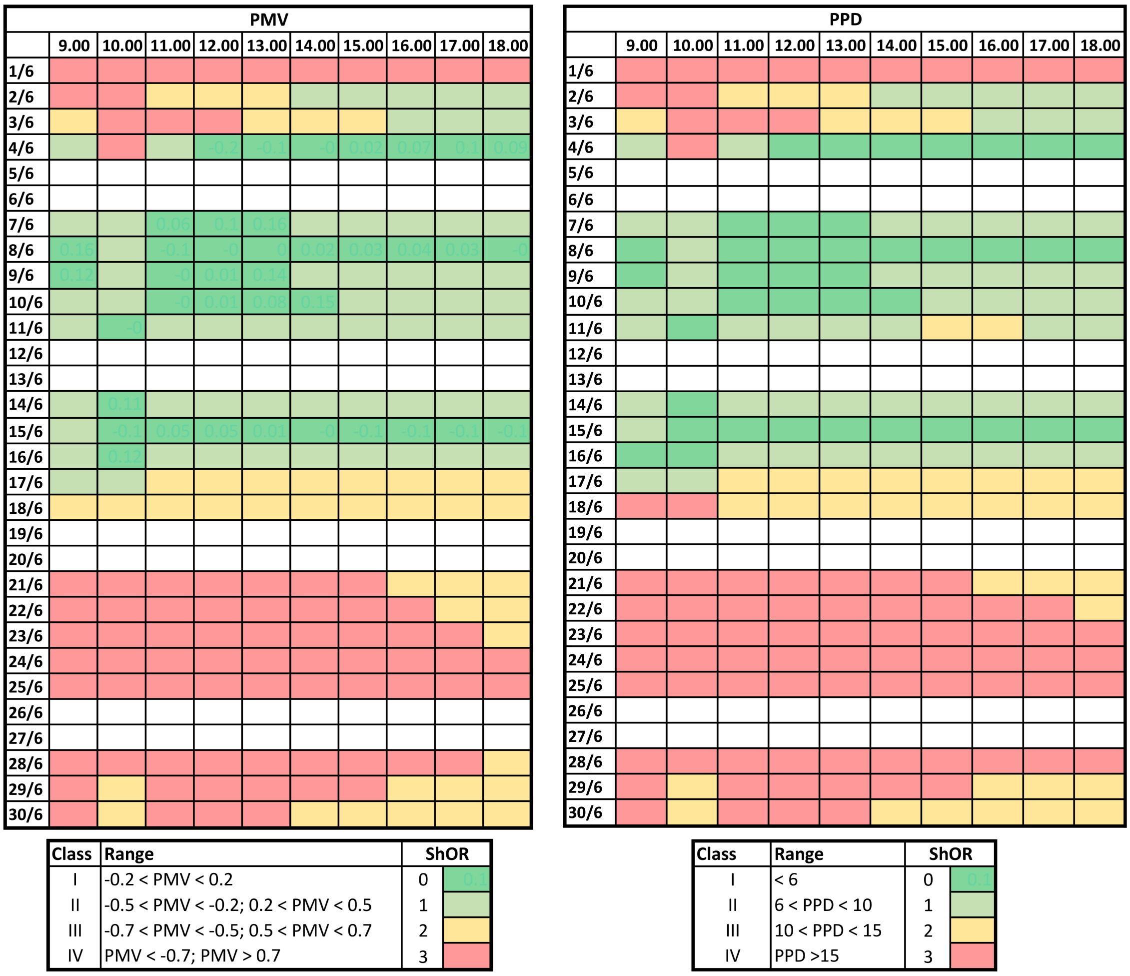


Figure 7.5: Severity of Dis-compliance for PMV and PPD indices.

Percentage Outside Range (POR) for Air temperature index

The Percentage Outside Range is now used to assess the impact that the Air temperature has on "Health and Well-being" for services related to Cooling domain. The assessment has been done checking when the air temperature in the office exceeded the range limit values defined for cooling season in ISO 7730:2005[71]. Consequently, due to the fact that the limit threshold has been exceeded no more than the 8 % of the occupied hours, the final score assigned is 2.

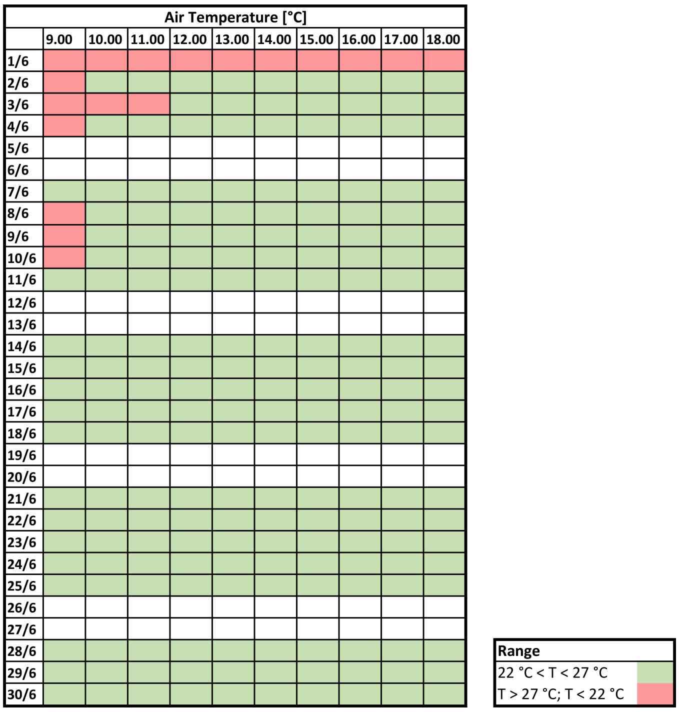


Figure 7.6: Hourly analysis for POR assessment of Air Temperature index.

Severity of Dis-compliance (SD) and Percentage Outside Range (POR) for air speed index

In this paragraph is explained the way in which the assessment for "Comfort" and "Health and Well-being" is carried out for services that belong to Controlled Ventilation domain. In this case study the air speed index is used both for "Comfort" and "Health and Well-being" because no hourly data are available regarding the CO_2 concentration in the interior space.

For what concerns impact on "Comfort" the Severity of Dis-compliance index was again used, checking with which degree of severity the Air speed has exceeded the thresholds defined for the classes. In this case, due to the fact that the air speed is set to 0.134 m/s and it has remained constant for the entire time-period, the SD index belongs to Class II, thus the score assigned is equal to 2.

On the other hand, for what concerns impact on "Health and Well-being" the Percentage Outside Range was used to check the amount of working hours in which the air speed has exceeded the maximum threshold values defined in Chapter 6 and in ISO 7730:2005[71]. Also in this case, due to the fact that the air speed is set to 0.134 m/s and it has remained constant for the entire time-period, the index has never been exceeded the limit values, thus the POR is equal to 0 % and the score assigned results in 3.

Air speed [m/s]										
	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00
1/6										
2/6										
3/6										
4/6										
5/6										
6/6										
7/6										
8/6										
9/6										
10/6										
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23/6										
24/6										
25/6										
26/6										
27/6										
28/6										
29/6										
30/6										

Class	Range	ShOR	
I	v < 0.12 m/s	0	
II	0.12 < v < 0.19 m/s	1	
III	0.19 < v < 0.24 m/s	2	
IV	v > 0.24 m/s	3	

Figure 7.7: Severity of Dis-compliance related to Air speed.

Long-term Daylight Factor assessment from EN 17037:2018

The Daylight Factor is chosen to assess the impact on "comfort" for services belonging to the Dynamic Envelope domain. In order to evaluate it over the entire month, EnergyPlus has extracted hourly illuminance value on the reference point in the workplane and for each time-step is computed the DF. Afterwards, using prescriptions given by EN 17037:2018[69] the percentage of time and surface in which the DF exceeded the limit value has been checked. This value is equal to the minimum suggested from the aforementioned Standard, i.e. DF > DT for 50 % of time for 50 % of the considered surface, as showed in Fig.7.9.

Consequently, the final score assigned results in 1, because the index meets the minimum requirements.

Percentage Outside Range (POR) for Daylight Glare Index (DGI)

To assess the impact on "Health and Well-being" regarding the Dynamic Envelope's services the Percentage Outside Range about the DGI is used. The acceptable limit value for this index is set to 22, thus all the hours in which this value is exceeded are marked as red, on the contrary they are marked as green, as showed in Fig.7.10. Consequently, since there were not hours outside the defined range, the score obtained is 3.

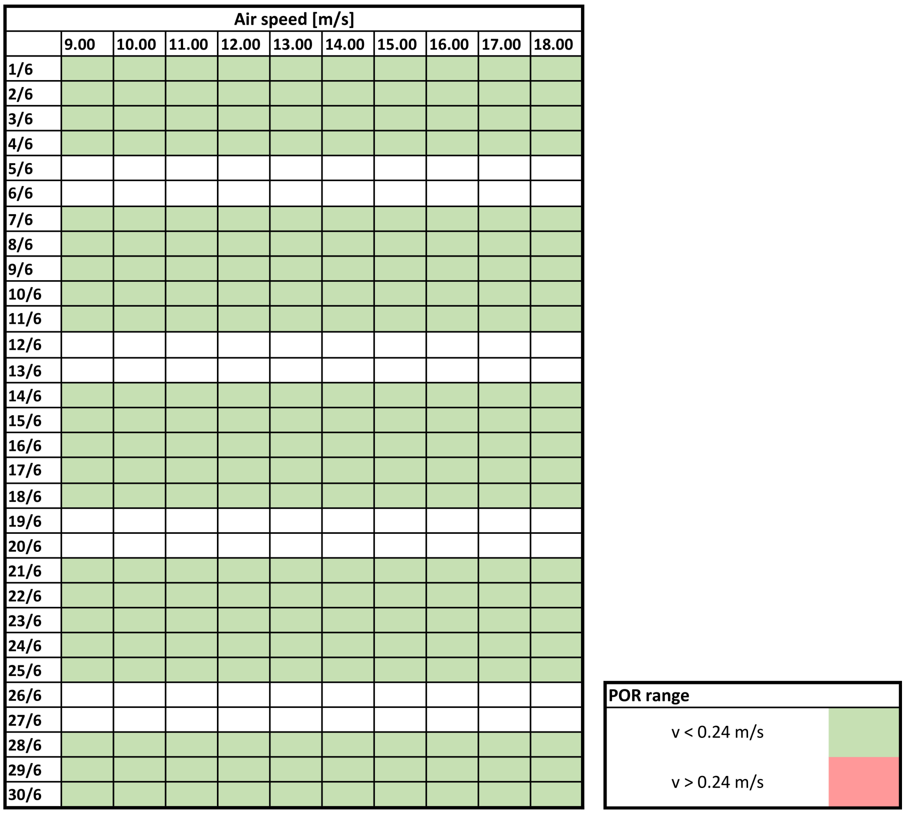

Figure 7.8: Hourly analysis for the assessment of POR related to Air speed.

The final scores from Key Performance Indicator Long-term assessment

As explained for the Steady-state evaluation, the ultimate score for each Impact Criteria for the considered technical domains is computed as an average between the score given by the SRI methodology, due to the level of functionality implemented in the building, and the score resulting from the KPIs assessment. Therefore, the final scores are showed in the summary table reported below (see Table7.5).

7.2.3. The final SRI scores

For this case study the final SRI score has been computed using not only the new weighting factors and the scoring methodology proposed in the previous Chapter and sections, but also using the official one proposed in the Final Report, aiming to understand and underline the main differences between the two approach and to evaluate the obtained results.

The final SRI score is also proposed for the two assessment method types explained in Chapter 6, i.e. Steady-state assessment, obtaining an SRI score per hour and the Long-term evaluation, obtaining an overall SRI score that takes into account the average performance during the assessment period.

From Table7.6 and Table7.7 it can be noticed that while for the Standard SRI methodology the final score is always the same, the Steady-state assessment gives different SRI

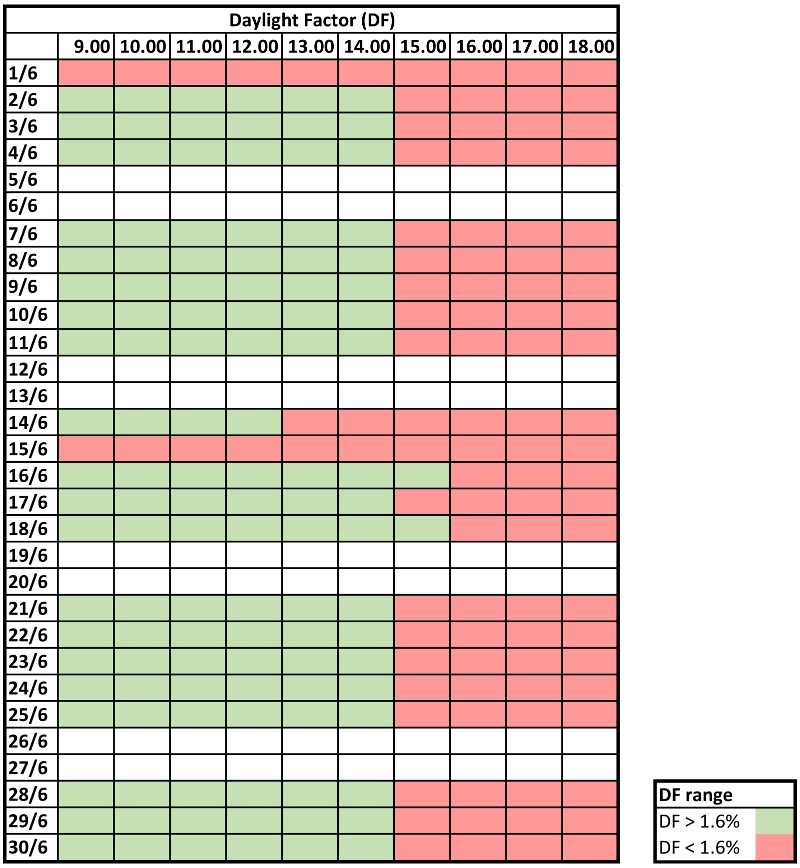

Figure 7.9: Hourly analysis for the Daylight Factor index.

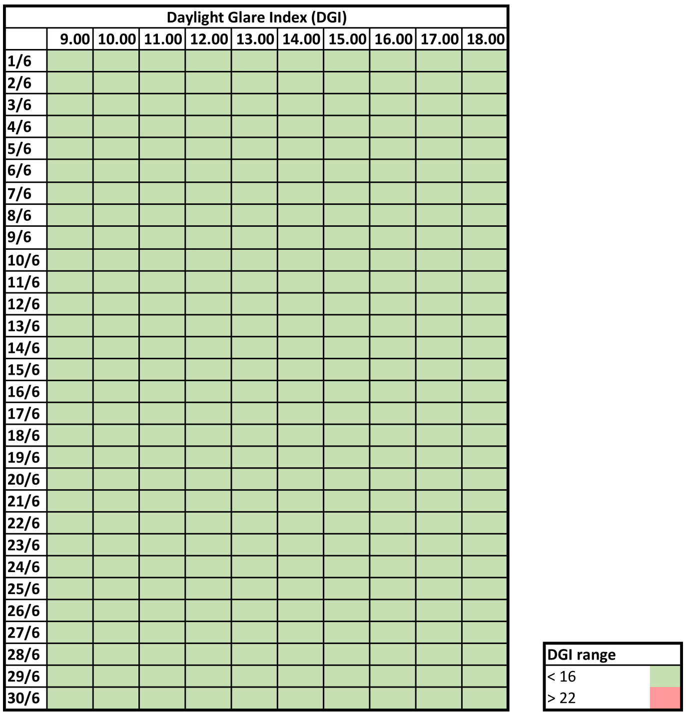

Figure 7.10: Hourly analysis for the assessment of POR related to Daylight Glare Index.

Service	**Code**	**Functionality level**		**Impacts**	
				Comfort	H&WB
Cooling emission control	Cooling-S1	level 2	Individual room control.	1	2
Generator control for cooling	Cooling-S2	level 3	Variable control of cooling production capacity depending on the load and external signals from grid.	2	-
Flexibility and grid interaction	Cooling-S3	level 3	Cooling system capable of flexible control through grid signals.	2	-
Air flow control	Ventilation-S1	level 2	Occupancy detection control.	2	3
Reporting information regarding IAQ	Ventilation-S2	level 0	None.	-	2
Window solar shading control	DE-S1	level 0	No sun shading or only manual operation.	1	2

Table 7.5: Final scores assigned to each domain's service based on mean between the score achieved by the KPIs long-term assessment and the score given from the SRI methodology.

values according to the real indoor conditions (see also Fig.7.11).

Moreover, looking at Table7.8 in which a detailed comparison is carried out for a specific instant during the entire day, the relative score related to "Comfort" computed with the original methodology overestimates the effective indoor conditions. Indeed, the two relative scores are significantly different.

On the other hand, for what concerns "Health and Well-being", the relative score computed using the Final Report's methodology greatly underestimates the score obtained assessing the real indoor conditions.

However, the final SRI score for both New and original SRI methodology are quite similar, respectively 65.79 % and 64.39 %, both belonging in class C.

A great difference in the final SRI score is achieved using the Long-term assessment.

June 21st		
Time	SRI score	SRI class
9.00	66.54 %	C
10.00	66.54 %	C
11.00	66.54 %	C
12.00	65.79 %	C
13.00	66.37 %	C
14.00	66.37 %	C
15.00	66.20 %	C
16.00	69.18 %	C
17.00	69.18 %	C
18.00	69.18 %	C

Table 7.6: SRI scores computed with the Steady-state assessment method and using the new proposed methodology.

June 21st		
Time	SRI score	SRI class
9.00	64.39 %	C
10.00	64.39 %	C
11.00	64.39 %	C
12.00	64.39 %	C
13.00	64.39 %	C
14.00	64.39 %	C
15.00	64.39 %	C
16.00	64.39 %	C
17.00	64.39 %	C
18.00	64.39 %	C

Table 7.7: SRI scores computed with the official methodology proposed in the Final Report[41].

Also in this case, the relative scores associated to "Comfort" and "Health and Well-being" greatly differ the ones from the others.

The same behaviour can be noticed for the final score, with a 72.00 % and a Class B applying the new methodology and a 64.39 % using the original one.

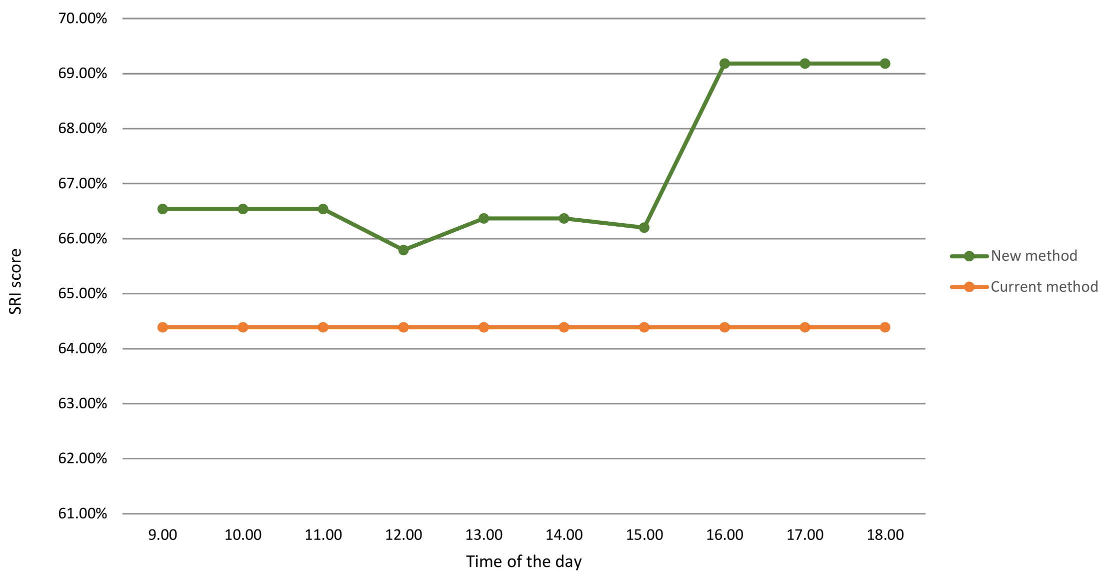

Figure 7.11: Differences in SRI score computed using the current methodology and the one computed with the new approach for the examined case study.

New methodology - h. 12.00		Official SRI methodology	
Impact Criteria	Relative score	Impact Criteria	Relative score
Energy savings on site	60.56 %	Energy savings on site	60.56 %
Flexibility for the grid and storage	94.86 %	Flexibility for the grid and storage	94.86 %
Comfort	48.21 %	Comfort	65.00 %
Convenience	55.26 %	Convenience	54.55 %
Health & Well-being	64.89 %	Health & Well-being	47.06 %
Maintenance & fault prediction	12.06 %	Maintenance & fault prediction	12.06 %
Information to occupants	28.37 %	Information to occupants	19.66 %
SRI score 65.79 %		SRI score 64.39 %	
SRI Class C		SRI Class C	

Table 7.8: SRI scores computed with the Steady-state assessment method, using the new proposed methodology, and with the official SRI methodology from Final Report[41].

New methodology		Official SRI methodology	
Impact Criteria	Relative score	Impact Criteria	Relative score
Energy savings on site	60.06 %	Energy savings on site	60.06 %
Flexibility for the grid and storage	94.86 %	Flexibility for the grid and storage	94.86 %
Comfort	84.62 %	Comfort	65.00 %
Convenience	49.18 %	Convenience	54.55 %
Health & Well-being	84.03 %	Health & Well-being	47.06 %
Maintenance & fault prediction	12.06 %	Maintenance & fault prediction	12.06 %
Information to occupants	13.20 %	Information to occupants	19.66 %
SRI score 72.00 %		SRI score 64.39 %	
SRI Class B		SRI Class C	

Table 7.9: SRI scores computed with the Long-term assessment method, using the new proposed methodology, and with the official SRI methodology from Final Report[41].

8. Conclusions

In the first chapters were given basic concepts useful to understand the development process of the Smart Readiness Indicator and its possible improvement actions. Introduced in 2018 by the EPBD, this index aims to evaluate the smart readiness of buildings across Europe, intended as the capability to use ICTs in order to adapt the operational phase to users' needs and the grid.

On the other hand, another key concept introduced at the beginning of this thesis work is the Indoor Environmental Quality (IEQ), which could play an important role in the SRI methodology for what concerns the key capability "Respond to users' needs".

However, the actually implemented methodology for the Smart Readiness Indicator does not fully exploit the potential deriving from the combination of the aforementioned introductory concepts, limiting itself to compute scores and impacts on categories involved with comfort and occupant's health only using the services' automation degree, i.e. levels of functionality. This behaviour can lead to an overestimation or underestimation of the effective indoor conditions, directly involving the occupants' health and well-being.

This thesis work started developing from the combination of the core concepts, focusing directly on the users' needs. Moreover, this decision is related with a background in Architectural studies, which are more familiar with Comfort and Well-being issues, providing a practical and specific contribution to the occupants' needs sphere and to the research field considered.

Through the use of Key Performance Indicators (KPIs) it has been proposed to evaluate the indoor conditions without totally replacing the actual implement methodology for the triage process. Indeed, all the final services' scores are computed as an arithmetic mean between the reached KPI value and the level of functionality really implemented in the building for the considered service. As result, two main assessment method has been proposed for the SRI evaluation: the Steady-state, using short-term KPIs and generating a dynamic SRI score, the Long-term evaluation, using long-term KPIs and producing a final SRI score that takes into account the overall building performance over a defined period.

On this matter, the case study has showed significant differences concerning the implementation of the new methodology and the original one from the Final Report, allowing to quantify the contribution of the new proposed approach. Indeed, the main differences has been observed in Impact Criteria's partial scores by validating the aforementioned underestimation or overestimation risk for effective indoor conditions.

For what concerns the determination of new weights for domains and impact criteria related to users' needs, the Analytic Hierarchy Process (AHP) has enabled the computation of of new weighting factors more consistent with the importance given to certain categories with respect to others. This analysis is carried out for a non-residential building type, involving a group of ten experts in this field. This MCDM method has been chosen because is able to combine the subjective component with a mathematical approach, leading to a more consistent results that better reflect the real priorities of a group of people.

The entire work meant to be a concrete contribution to the future developments of the Smart Readiness Indicator from the Italian side, giving an added value to the method already implemented by the European Commission, with a particular focus on the occupants and the Indoor Environmental Quality.

Future works might concern the improvement of what actually proposed in this work, with the determination of new weighting factors for all the building types and involving more experts in the decision-making procedure, changing the actual results and data in more consistent and representative ones for the Italian context.

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