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Pursuing occupants' health and well-being in building management: definition of new metrics based on indoor air parameters.

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Abstract: The spread of COVID-19 has affected the lives of millions of people. Pandemic has made people more sensitive to health issues. In particular, the growing concern of the virus spread in confined spaces has promoted the necessity to improve indoor air quality. Literature is stressing how buildings must be designed and operated pursuing occupants' health and well-being, with a particular attention for indoor air parameters. This poses the challenge of monitoring and assessing these aspects through proper metrics. In this paper the approach towards a multi-step assessment procedure embedding in buildings assessment health and well-being related variables and indicators is elaborated. They are intended to inform a building manager of the potential influence of air conditions on human health and well-being. Moreover, a set of monetary metrics (i.e., impacts) is proposed to translate energy and indoor air related building performances into euros, putting the basis for a comprehensive economic evaluation. The application of the set of proposed metrics to an Italian hotel (i.e., Italian pilot of H2020 MOBISTYLE project), enabled to map some indoor air conditions causing health concerns, and to identify clusters of guests with best and worst indoor air conditions, to be targeted by new management strategies. Despite case study specific limitations, the application exemplified how the methodology can expand the traditional energy-based

performance assessment for building management towards indoor air domain and the related economic impacts, with implication on results in terms of overall economic performance of the building from both a private and public perspective.

Keywords: healthy building, health, well-being, Key Performance Indicators, indoor air quality, cost-benefit analysis

1. Introduction

The importance of preserving proper indoor environmental quality while reducing energy consumptions in buildings is well recognized. Nowadays, the attention is shifted from the topic of indoor environmental quality to the broader concept of human health and well-being as influenced by indoor space, with a particular attention for Indoor Air Quality (IAQ) and ventilation. According to the so-called human-centric approach, recent literature, as well as the reviewed EPBD, stresses how buildings must be designed and operated coupling sustainability goal (e.g., reduction of energy consumptions) to comfort and occupants' health [1]. Thus, today it is common to speak about "healthy buildings", defined as "built structure that promotes the positive well-being of individuals [1]. The design of healthy building should be based on nine foundations - ventilation, air quality, thermal health, moisture, dust and pests, safety and security, water quality, noise, lighting and views [2]. Despite IAQ is not the only determinant of healthy buildings [3], starting from the hygienic revolution (middle of XIX century) until today, health concerns have been more and more associated to air quality. In lack of clear evidence of harms produced by the indoor air, and despite more than half of the body's intake over life is air inhaled indoor, the focus has been for a long time on outdoor air [4]. Buildings, by producing emissions due to their energy consumptions, contribute to the outdoor air quality, but IAQ and building ventilation was not in the political agenda. In the last decades of the XX century things started to change, due to evidence of harmfulness of radon (late 1960s), formaldehyde (early 1970s), problems connected to dust and Sick Building Syndrome (SBS) related symptoms, e.g., headache, eye, nose, and throat irritation, fatigue, and dizziness and nausea (late 1970s), and an increase of cases of allergies [4]. Today, IAQ and ventilation are taken in great account in respect to public health issues and, starting from the first decade of the new century, focus on IAQ has been raised [5]. The growing attention for IAQ in relation to health was recently enhanced from the needs emerged during COVID-19 pandemic, stressing how much indoor environment management, IAQ and ventilation in particular, is no more only connected to the fulfilment of occupants' comfort, as it has been for many decades of the last century [4], but to preserve people health. This is consistent with the definition of IAQ, which is the quality of the air within buildings as it affects both comfort and health of building occupants. It mostly depends on the presence of indoor pollutants, which can produce harms to humans [7]. However, IAQ is also relevant in terms of its sensitivity impacts, determining occupants' perceived quality, and affecting their overall comfort and well-being. In this sense, IAQ perception is influenced by various indoor parameters (i.e., indoor air temperature and relative humidity) [8], whose control towards occupants' comfort might be realized thanks to the same systems responsible for ventilation. Given the dual role of IAQ and according to the definition of healthy buildings, indoor spaces should not only prevent people from being harmed, but also enhance their comfort and well-being. Thus, there is a need for combining perception/comfort-based indicators for indoor environmental performance assessment, with health-based ones, able to support the design of healthy buildings by taking into consideration impacts of indoor air conditions on human health and well-being.

But how to monitor and assess occupants' health and well-being as influenced by IAQ and related parameters? If air quality is concerned, ventilation was traditionally used as a proxy for indirect IAQ assessment and as strategy for its management to achieve, first of all, people comfort. Similarly to thermal domain, IAQ-related comfort is measured in terms of achieved comfort category (from I to IV) [9], which corresponds to a percentage of people dissatisfied with IAQ, usually quantified as function of fresh air flow rate or CO_2 concentration above outdoor level [10]. Today, requirements for both perceived IAQ and health in the occupied zones can be based on predefined minimum ventilation air flow rate (method 3 of EN 16789-1 [11]), and ventilation rate is the most frequently used parameter to assess IAQ in Green Building certification schemes [12]. Scientific evidence about the influence of IAQ on people performance brought to the definition of less traditional indicators for people well-being, like productivity [13], sick leaves [14],[15], etc., which were found to be related to ventilation rate and indoor air temperature. Indeed, similar studies were conducted in relation to thermal quality of the indoor environment (not independent from ventilation), as summarized by [16], adding to the previous list of metrics for the assessment of occupants' satisfaction also, e.g., the number of complaints for thermal discomfort [17]. The quantification of this metrics is based on monitored indoor parameters and it is possible thanks to the adoption of models reported in literature, well summarized by [18] and [19]. However, current literature is mostly focused on measuring statistical correlations between certain indoor parameters and reported diseases, without providing yet for models which permit to predict specific diseases by knowing indoor parameters status.

For example, if SBS is concerned, [20] demonstrated as there are various indoor parameters which show a significant correlation with the incidence of those symptoms. In particular, airborne particulates were always strongly associated with all symptoms, thus air-conditioned buildings could provide a healthy and comfortable environment. According to the study of [21] on mucous membrane symptoms and lower respiratory irritation in 100 office buildings, , CO_2 is approximately correlated with other indoor pollutants that may cause SBS symptoms, even if there is no direct causal link between exposure to CO_2 and SBS symptoms. Concerning ventilation, [22] provided for a model to quantify the change in SBS symptoms prevalence based on ventilation rate. Despite the limitations reported by the authors, the analyses indicate that ventilation rates may have a considerable influence on the prevalence of SBS symptom. Their correlation with a number of indoor parameters traditionally related to thermal comfort in offices was studied by [23], who concluded that higher winter indoor temperatures are associated with increases in all the analysed symptoms, while higher summer temperatures, above 23°C, were associated with decreases in most of them. Despite most of the studies involve offices [21][22][23] and schools [24][25], examples on the residential built stock are also available [26]. Focusing on what [2] defines "thermal health" (i.e., encompassing "all of the impacts of thermal conditions on health"), the list of evidence of impacts of indoor air parameters (correlated to IAQ and ventilation) on human health and well-being can be enlarged. A study conducted in the European context concluded that workers experienced itchy, watery eyes, headaches, and throat irritation when non-favourable thermal conditions occurred [27]. Moreover, too warm indoor environment was related to an increase in SBS symptoms, negative moods, heart rate, respiratory symptoms, and feelings of fatigue by [28]. Temperature and relative humidity were also found to influence diseases transmission [29]. Indeed, some types of viruses can stay in the air for longer under cold and dry conditions. On the contrary warm and humid spaces are favourable for mould and fungal growth [30].

These and other studies give an understanding of which are the parameters potentially responsible for some of the reported diseases, paving the way to future research and to the definition of appropriate metrics for the monitoring, assessment and, finally, improvement of indoor space quality in respect to human health and well-being. Indeed, despite all the scientific evidence on the impacts of buildings indoor air on people health, there is still a gap in our ability of translating this knowledge into actionable guidelines for policy makers, building managers and occupants to reduce health risks and enhance occupants' well-being [1]. Thus, proper metrics are needed. Measurable metrics are also the first step towards the assessment of the so-called co-benefits brought by healthy buildings. The need for including in the evaluation process new metrics, e.g., environmental impacts, comfort, health etc., has been the reason for shifting from pure financial assessment methods of design scenarios (e.g., the cost-optimal analysis), accounting for monetary costs and revenues/savings, to economic evaluation ones [31]. Between the latter, the Cost-Benefit Analysis (CBA) is particularly relevant, being an analytical tool for judging the economic advantages and disadvantages of an investment decision by assessing its costs and benefits, which are priorly monetized and distributed over time. Monetizing such co-benefits can put the basis for a comprehensive economic assessment of interventions aiming at healthy spaces, enhancing the spreading of the needed technologies (i.e., filtering systems, sensors, etc.) [32].

H2020 MOBISTYLE EU project (2016-2020) can be considered as anticipatory of these topics, since it put health and well-being at the centre of the proposed strategy. The aim of the project was to push a behavioural chance, providing actionable tasks to buildings occupants in order to help them building their own indoor environment, saving energy with positive impacts on their health and well-being [33]. For this purpose, ICT-tools and awareness campaigns were developed for different targeted users, represented by several pilots (i.e., residential and non-residential buildings) across Europe. The knowledge provided by the tools came from quantitative data, i.e., easy-to-understand Key Performance Indicators (KPIs) based on monitored data, whose collection was possible thanks to monitoring systems. Monitored data, paired with qualitative data (i.e., surveys), also allowed to assess the overall project impacts by comparing the performances of the buildings in terms of energy consumptions and IEQ before and after MOBISTYLE strategy introduction in the pilots, also accounting for co-benefits due to saved energy and improved IEQ. Their monetization in the framework of a CBA opened the opportunity to compare them with costs for the technologies enabling such strategy [32]. The attention for health and well-being was expressed within the project via specific KPIs (also part of the CBA), advice (displayed to the buildings' occupants via ICT and non-ICT tools), and an experimental setting [34].

Given the need for metrics to monitor and assess occupants' health and well-being, this paper wants to contribute by dealing with indoor air parameters that have an implication in this sense. Starting from H2020 MOBISTYLE ideas, an approach towards a multi-step assessment procedure embedding in buildings assessment new health and well-being related metrics is elaborated in respect to hotels (section 2). Results presented in this paper are intended to exemplify the methodology using monitored data from the Italian pilot of H2020 MOBISTYLE project (section 3). In conclusion, limitation and future development are also depicted (section 4).

2. Material and methods

In the vein of the topic of healthy spaces, in this section a multi-step methodology for building performance assessment based on multiple metrics is introduced, focusing on hotels rooms. The decision of focusing on hotel rooms come from their potential representativeness also for residential indoor spaces, where people spend most of their time.

The set of tools and methods here introduced were firstly explored within the H2020 MOBISTYLE project, whose contribution to the topic was descried in introduction. The methodology aims at:

- Defining informative variables and figures (based on monitored parameters) for building management towards healthy buildings.
- Coupling traditional energy related KPIs with newly developed and easy to understand indoor air related KPIs.
- Defining a set of metrics as criteria for a comprehensive economic evaluation of project scenarios.

These points are further elaborated in the relevant sections in the followings (section 2.1). According to the focus of this research, a specific approach for the application of the methodology in hotel buildings is also proposed (section 2.2).

2.1. Methodology for multi-step building assessment

Pairing energy related KPIs (i.e., energy consumptions and energy intensity) with metrics that are informing the building manager on the building performance in respect to the potential influence of its air on human health and well-being is becoming possible thanks to scientific evidence of such influence and to the growing availability of data collected in buildings through monitoring systems. To build a synergy, it is fundamental to identify parameters which are relevant in terms of occupants' health and well-being, whose collection should be encouraged towards building management practices attentive to these topics.

A first level of building performance assessment attentive to health and well-being concerns is based on the analysis of the involved monitored parameters and on the definition of several hourly variables whose aim is translating such data into health and well-being relevant mono-parametric metrics, which must be considered beside the energy related one.

The second level of assessment is represented by indicators (i.e., KPIs), which aim at combining multiple parameters to give an overall performance score to the indoor air. The proposed daily KPIs are based on indoor air parameters measured in the indoor environment (i.e., hotel rooms). The same KPIs can be computed as daily averages across a certain computation timespan, preferably a season, for benchmarking. A better representativeness of benchmark values can be obtained by isolating some contextual variables, like occupancy type in hotels. For this reason, the multi-step methodology presented in this paper is coupled with a clustering approach of occupant types, for which KPIs, as well as impacts (see next step) can be computed as benchmarks for future assessments (section 2.2).

The third level of assessment supports economic evaluation of possible design strategies, since it consists of a set of monetary metrics. Their assessment is based on the quantification and monetization of identified economic impacts of the building performance, also deploying models available in literature. This level of assessment enables to combine energy and indoor air domains, since all the metrics are reported in the same unit of measurement, namely euros, and can then be summed. These monetary metrics, representing economic impacts of energy and indoor air related performances (as assessed via the KPIs identified in the previous step), can be used to assess investments decisions/strategies in terms of their benefits for the occupants and the manager of the building, to be compared with the costs necessary for their realization. One of the tools typically deployed for this purpose is the CBA [32]. According to the CBA, impacts must be identified and compared with a counterfactual scenario, where investments under evaluation are not deployed. Quantification of the impacts under project and counterfactual scenarios enables to identify whether the project brought benefits (minimizing negative impacts and maximizing positive ones) or not. In this paper a set of impacts, which are representing the criteria for possible project evaluation, are defined together with their quantification and monetization methods, specifying whether they must be minimized or maximized by a potential project to bring benefits. To be part of a CBA framework they are meant to be assessed in pre and post project scenario, which goes beyond the scope of this paper. This was done in [35].

The aforementioned three levels are depicted in Figure 1, where the proposed variables, indicators and impacts are mapped.

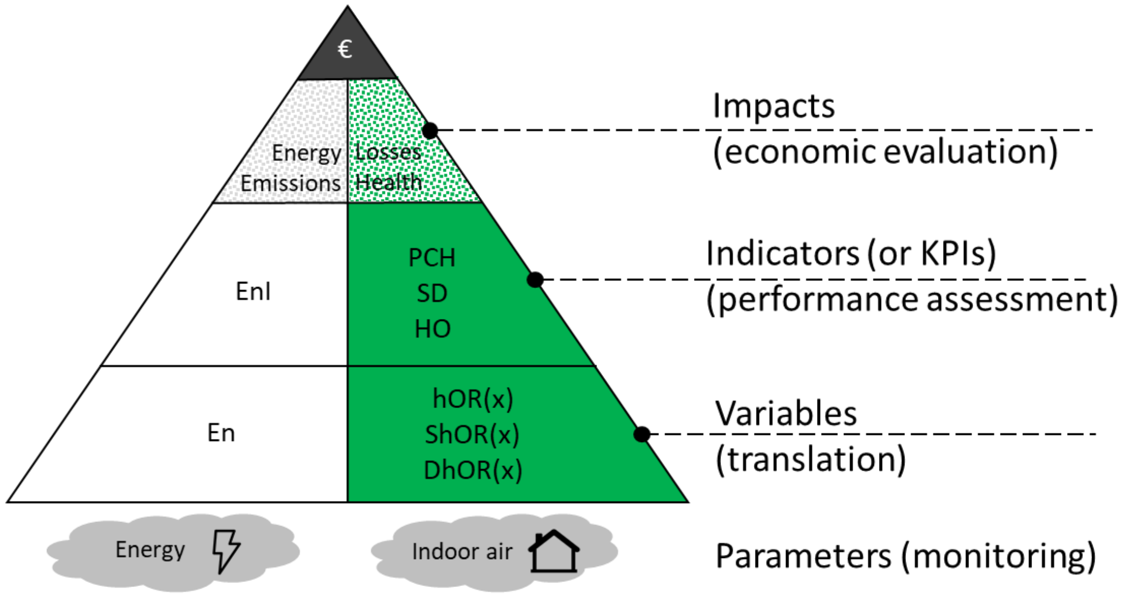


Figure 1 – Schema of the methodology for multi-step building assessment.

In Figure 1, the pyramidal shape wants to represent the concept of a building performance assessment procedure, built on top of energy and indoor air related monitored data, which is progressive (from individual monitored parameters to a single metric, expressed in euros), multi-domain (indoor air variables and indicators are paired with traditional energy related ones) and health-and-well-being-driven (all the metrics to be coupled with energy related ones are defined based on their relevance in respect to people health and well-being). Filled areas of the pyramid represent the innovation of this methodology, which expands the traditional energy-based performance assessment for building management (represented by white areas) to the indoor air domain (green areas, despite type of filling) and to energy and indoor air related economic impacts (dots-filled areas, despite colour). Involved parameters and proposed metrics are elaborated in the following subsections per each assessment level.

2.1.1.Parameters

Priorly to the definition of health and well-being related metrics to be paired with energy related ones, it is important to identify parameters that are relevant in this sense, whose collection through buildings monitoring systems must be encouraged. In this research several criteria for their selection were adopted. Parameters:

- must be relevant in terms of their influence on human health and well-being.
- must be related to indoor air.
- collection in buildings must be financially and technically feasible deploying technological solutions already available in the market.
- sensing devices must be suitable for continuous monitoring strategy.

While the first criterium represents the core objective of the overall methodology, the second one is consistent with the focus of H2020 MOBISTYLE project and, most importantly, with the fact that health concerns have been more and more related to air quality across the last 50 years (see introduction). The two criteria related to the technologies for data collection support an easy transfer of the methodology to management practices, and they were also adopted within H2020 MOBISTYLE.

To be paired with energy consumptions (measured in kWh), the followings indoor air related parameters were selected:

- CO_2 concentration [ppm]
- Indoor Air Temperature [°C]
- Indoor Air Relative Humidity [%]

CO_2 concentration is included as a proxy for ventilation effectiveness and indirect assessment of IAQ and its subsequent impacts on humans. Despite scientific evidence of the effects of specific pollutants (e.g., radon, formaldehyde, CO, etc.) on human health are available, their continuous monitoring in buildings for health-and-well-being-based management is not technically and/or economically sustainable. The measure of ventilation rate in-situ is also a complex topic, which is usually performed via spot measurements and specific techniques, not compatible with a standing monitoring system. On the contrary, very well-established NDIR sensors enable the monitoring of CO_2 concentration in a reliable way. CO_2 at normal concentration does not have health implication itself, but, in spaces where occupants are the main sources of pollutants, it is a good predictor of occupants' satisfaction with IAQ, and it is correlated with other indoor parameters that might influence SBS occurrence, as mentioned in introduction.

In addition to CO_2 concentration, indoor air temperature and indoor air relative humidity are chosen as relevant parameters in this research. They are two out of the six parameters for the computation of PMV-PPD index, based on which thermal comfort categories (or classes) are defined [9]. However, they are included here because of their influence on IAQ and occupants' health and well-being. Indeed, when it comes to comfort or health issues due to poor IAQ, parameters which are traditionally related to thermo-hygrometric assessment also play a role. As demonstrated in the studies mentioned in [8], as a perceived phenomenon, IAQ level is influenced by temperature and relative humidity; a small percentage of dissatisfied with IAQ is observed at 18°C temperature and 30% relative humidity, but the dissatisfied rate tends to increase together with relative humidity, with a bigger slope for temperatures higher than 18°C. Studies have shown that warm and humid air is perceived as stuffy, and the higher the room temperature in winter, the higher the number of typical SBS symptoms. Moreover, as reported in [36] , it is possible to correlate the comfort-based categories of indoor environment (ranging from I-excellent to IV-poor) with health and well-being related concerns: if indoor environment category in terms of temperature is III or IV, a significant reduction in work performance and an increase in complaints on dry air and SBS symptoms in winter are observed. As long as relative humidity is concerned, [37], by reviewing the literature about the effect of low humidity not only on perceived IAQ, but also on sensory irritation symptoms in eyes and airways work performance, sleep quality, virus survival, and voice disruption, was able to assert that humidity level should become a meaningful IAQ descriptor [37].

The three selected parameters can be collected in indoor spaces through a single available, and reliable monitoring device.

2.1.2.Variables

Given the defined monitored parameters, the objective of the first step of the methodology is turning monitored data into understandable and health-well-being-relevant information for building management which must be considered beside energy related ones. To do so, three (times "x" parameters involved) variables for the indoor air domains are identified, beside to one (times number of involved energy carrier) traditional variables for the energy domain.

The energy variable (called **En**) is the **daily energy consumption** as monitored per each energy carrier thanks to dedicated sensors (i.e., electric meter, heat meter, gas meter, etc.).

En variable (or variables, in case more than one energy carrier is involved) is traditionally evaluated for building management. On the other hand, identified indoor air variables allow to add indoor air domain to the assessment, in the form of a set of metrics whose definition is based on the awareness of its influence on human health and well-being. Variables allow to infer health-and-well-being-aware quality label related to the indoor environment per each hour of a day. Hourly variables are:

- **Hour outside range in terms of parameter "x"- hOR(x)**: it refers to an hour where the parameter "x" is out of a pre-defined range (identified as thresholds for comfort class II). It can equal 1 (i.e., the hour is outside range) or 0 (i.e., the hour is characterized by the indoor parameter "x" within range).
- **Severity of hour outside range in terms of parameter "x" - ShOR(x):** it represents the severity of indoor air towards occupants' health and well-being in terms of the parameter "x".

It is a score ranging from 0 to 3 according to the range (i.e., thresholds borrowed from comfort classes) satisfied at each hour. In particular, comfort class I equals 0, class II equals 1, class III equals 2, while an hour of discomfort is scored 3. Thus, the variable can vary from 0 (not severe) to 3 (very severe).

- **Degree hours outside range in terms of parameter "x" - DhOR(x)**: it refers to the degrees over a certain threshold identified as the limit for overheating (i.e., 23°C). The variable equals 0 when the indoor temperature is equal or smaller than this threshold, otherwise it is major than 0.

"x" can be referred to T, RH or CO_2, where "T" means hourly mean indoor air temperature, "RH" means hourly mean indoor relative humidity, and "CO_2" means hourly mean CO_2 concentration computed from monitored data collected from xx:00 to xx:59. The mathematical conditions for their definition are reported in Table 1.

Table 1 – Indoor air variables: conditions and colour code

$\boldsymbol{hOR(x)_i}$ **, where x: (T, RH, CO_2)**	**Colour code**
$T_i < T(II)_{lim,\,low} \vee T_i > T(II)_{lim,\,up} \rightarrow hOR(T)_i = 1$;	
$T(II)_{lim,low} \leq T_i \leq T(II)_{lim,up} \rightarrow hOR(T)_i = 0$	
$RH_i < RH(II)_{lim,\,low} \vee RH_i > RH(II)_{lim,\,up} \rightarrow hOR(RH)_i = 1$;	
$RH(II)_{lim,low} \leq RH_i \leq RH(II)_{lim,up} \rightarrow hOR(RH)_i = 0$	
$C_{CO_{2\,i}} > CO_2(II)_{lim} \rightarrow hOR(CO_2)_i = 1$;	
$C_{CO_{2\,i}} \leq CO_2(II)_{lim} \rightarrow hOR(CO_2)_i = 0$	
$\boldsymbol{ShOR(x)_i}$**, where x: (T, RH, CO_2)**	**Colour code**
$T(I)_{lim,\,low} \leq T_i \leq T(I)_{lim,\,up} \rightarrow ShOR(T)_i = 0$;	
$T(II)_{lim,\,low} \leq T_i < T(I)_{lim,\,low} \rightarrow ShOR(T)_i = 1$;	
$T(III)_{lim,\,low} \leq T_i < T(II)_{lim,\,low} \rightarrow ShOR(T)_i = 2$;	
$T_i < T(III)_{lim,\,low} \vee T_i > T(III)_{lim,\,up} \rightarrow ShOR(T)_i = 3$	
$RH(I)_{lim,\,low} \leq RH_i \leq RH(I)_{lim,\,up} \rightarrow ShOR(RH)_i = 0$;	
$RH(II)_{lim,\,low} \leq RH_i < RH(I)_{lim,\,low} \vee RH(I)_{lim,\,up} < RH_i \leq RH(II)_{lim,\,up} \rightarrow ShOR(RH)_i = 1$;	
$RH(III)_{lim,\,low} \leq RH_i < RH(II)_{lim,\,low} \vee RH(II)_{lim,\,up} < RH_i \leq RH(III)_{lim,\,up} \rightarrow ShOR(RH)_i = 2$;	
$RH_i < RH(III)_{lim,\,low} \vee RH_i > RH(III)_{lim,\,up} \rightarrow ShOR(RH)_i = 3$	
$C_{CO_{2\,i}} \leq CO_2(I)lim \rightarrow ShOR(CO_2)_i = 0$;	
$CO_2(I)_{lim} < C_{CO_{2\,i}} \leq CO_2(II)_{lim} \rightarrow ShOR(CO_2)_i = 1$;	
$CO_2(II)_{lim} < C_{CO_{2\,i}} \leq CO_2(III)_{lim} \rightarrow ShOR(CO_2)_i = 2$;	
$C_{CO_{2\,i}} > CO_2(III)_{lim} \rightarrow ShOR(CO_2)_i = 3$	
$\boldsymbol{DhOR(x)_i}$ **, where x: (T) and T_{over}=23°C**	**Colour code**
$T_i \leq T_{over} \rightarrow DhOR_i = 0$	
$T_i > T_{over} \rightarrow DhOR_i = (T_{over} - T_i)$	

NB: i refers to each hour whose performance in terms of indoor air are intended to be translated into these variables.

Upper and lower limits (identified with "lim" subscript in Table 1) for hOR(x) and ShOR(x) variables are borrowed from comfort classes (identified by Roman numerals from I to III in brackets). Thus, their values vary according to season, use of the space, presence of cooling system, etc., as defined in [9]. Despite the reference to thermal comfort classes limits, the reasoning for their definition is health and well-being related. Indeed, according to literature (see also section 2.1.1), comfort classes were found to be correlated with a difference in level of reported SBS, particularly critical above class II, on which hOR is based. Limit for winter overheating, instead, is defined as 23°C according to literature [23], as further explain later in this paper (section 2.1.3).

The variables can be translated into a graphical information through carpet plots. Indeed, once each hour of a day is labelled via the conditions reported in Table 1, the hourly variables can be visualized based on the colour codes specified in the same Table. Examples are proposed with results (section 3).

2.1.3. Indicators

While the variables defined in the previous section are intended to translate monitored parameters into understandable metrics, the definition of normalized or multi-parameters indicators addressed in this section supports the assessment of performances of the system in an aggregated way. Accordingly, three indicators for indoor air domain are proposed, beside one indicator identified as traditional for the energy domain.

The identified energy indicator (called **EnI**) is the **daily energy intensity** computed as daily consumptions of each energy carrier divided by the number of hotel rooms. This indicator (or indicators, in case more than one energy carrier is involved) is traditional in building performance assessment for hotels [38]. On the contrary, for indoor air domain, newly developed KPIs are proposed in this research. Daily indicators are:

- **Percentage of compliant hours - PCH:** it is a daily average (considered all ”x” parameters) percentage of hours compliant to ranges (i.e., comfort class II per each parameter ”x”) and can vary from 0% to 100%. It aims at measuring for how much of the time indoor conditions are not likely to compromise occupants' well-being. It is computed starting from hOR(x).
- **Severity of dis-compliance - SD:** it is a daily average (considered all ”x” parameters) score of indoor air status severity and can range from 0 (compliant with ranges) to 3 (severely out from ranges). It aims at measuring how severe the indoor conditions towards human well-being according to certain ranges (i.e., comfort classes from I to IV) are. It is computed starting from ShOR(x).
- **Overheating - OH:** it refers to daily degree hours above a certain temperature threshold which identifies the phenomenon of overheating. It can equal 0°Chour if no overheating occurs over the day, and range till a maximum value only bounded to what it is physically possible. It is computed starting from DhOR(x).

All KPIs refer to occupied hours (i.e., Oh), which can be assumed from literature, assessed from data analysis of certain parameters collected in the building, or reported from the building manager. KPIs are described further in the followings.

The **percentage of complaint hours** indicator (called **PCH**) is defined as the average percentage of hours when indoor conditions, being complaint to certain ranges (i.e., limits for comfort class II), are not likely to compromise occupants' well-being. Indeed, outside the comfort classes II, there are more evidence about possible health impacts than within the ranges of that class. Hours when parameters ”x” are outside thresholds for comfort class II are known, per each occupied hour of a day, in terms of hourly hOR(x) variable. PCH is computed as weighted sum of percentage of hours in class II according to the measured parameters "x" over occupied hours of a day (i.e., PCH(x)). The higher the percentage is, the better the indoor quality and the least the risk for issues with occupants' well-being.

$$PCH(x) = \frac{Oh - \sum_{i=1}^{Oh} hOR(x)_i}{Oh} \quad [\%] \quad where\ x: (T, RH, CO_2)$$

$$PCH = \alpha_1 PCH(T) + \alpha_2 PCH(RH) + \alpha_3 PCH(CO_2) \quad [\%]$$

To measure the **severity of dis-compliance**, another KPIs is defined, which is called **SD**. Severity in terms of each of the monitored parameters "x" is known, per each occupied hour of a day, as hourly ShOR(x) variables. Thus, a daily average ShOR(x) variable per each parameter "x" is computed (i.e., SD(x)). SD (severity of dis-compliance) indicator is computed as the weighted sum of daily average score assessed in terms of ShOR(x) computed on occupied hours per each monitored parameter "x" (i.e., SD(x)).

$$SD(x) = \frac{\sum_{i=1}^{Oh} ShOR(x)_i}{Oh} \quad [0-3] \quad where\ x: (T, RH, CO_2)$$

$$SD = \alpha_1 SD(T) + \alpha_2 SD(RH) + \alpha_3 SD(CO_2) \quad [0-3]$$

Both the above mentioned KPIs provide added information on the overall quality of indoor air status expressed in easy-to-understand units to be displayed to the building manager and to the occupants. In this work, each addend of the equations defining PCH and SD, is considered to have the same weight ($\alpha_1 = \alpha_2 = \alpha_3 = 1/3 = 0.333$).

A third indicator is proposed, which captures and quantifies a specific cause for health concerns in buildings, which is the phenomenon of **overheating** (i.e., OH indicator). Indeed, according to some studies [23], incidence of headache cases, which are reported within the set of the so called SBS symptoms, are associated to the phenomenon of overheating. In particular, headache incidence is correlated to the degree hours above a certain temperature threshold (i.e., 23°C). By knowing the degrees over the same threshold per each hour of a day (i.e., DhOR(T) variable), OH is computed in the occupied hours (i.e., Oh) as follows:

$$OH = \sum_{i=1}^{Oh} DhOR(T)_i \qquad [Degree - hours]$$

2.1.4. Impacts

The third step of the methodology is based on a set of identified metrics whose deployment could support the combination of energy and indoor air domain in building performance evaluation, by referring to the same unit of measurement, namely euros. At the basis of their definition there is the identification of the economic impacts of energy and indoor air performances of buildings (as assessed via KPIs from section 2.1.3), which are then monetized. These monetary metrics, when computed under current and design scenarios, can be used as criteria to assess investments decisions/strategies.

Identifying economic impacts requires to assume a certain perspective. In this research, two perspectives are identified - the private one, namely the hotel manager, and the public one, which refers to the whole society.

Table 2 provides the list of the impacts, together with the appraisal method for their monetization. Their prior quantification is supported by specific KPIs defined above (subsection 2.1.3), as underlined in Table 2 (column "KPI"). The aim of a potential project against each of the impacts is also specified.

Table 2 – Economic impacts

Perspective	Domain	KPI	Impact	Aim	Appraisal method
Private	Energy	EnI	**Energy** (i.e., bills)	Minimize	Energy cost
	Indoor Air	PCH and/or SD	**Losses** (i.e., renting)	Minimize	HPM
Public	Energy	EnI	**Emissions** (i.e., PM)	Minimize	PM cost
	Indoor Air	OH	**Health** (i.e., headache)	Minimize	COI

From the private point of view (i.e., hotel manager), the energy performance of a building, assessed through EnI indicator, has an economic implication in terms of costs for the provision of the energy carriers. In this research this impact is named "Energy", its quantification is possible by knowing energy intensity of the building (namely EnI indicator, or indicators, in case more than one energy carrier is involved), and the monetization requires to multiply consumptions times the energy cost of each carrier. By enlarging the scope of the assessment to the indoor air domain, it is possible to say that the condition of the indoor air influences the building economic performance in terms of the quality of provided service. In hotels, this is represented by the stay, which from the manager point of view have a certain economic value (i.e., price per night). Literature shows that guests are willing to pay more in face of improved indoor conditions [39], thus, an economic implication of poor indoor air quality is represented by the missed incomes that the hotel manager has from the rooms renting. The higher the quality of indoor air is (high PCH and low SD), the more the guests would be willing to pay for the stay and the higher the incomes for the hotel manager would be. Thus, "Losses" is referred to the economic impact of sub-excellent indoor air conditions, which cause a missed gain. This missed gain is quantified as people willingness-to-pay (WTP) for improved indoor environmental condition in hotel rooms. WTP is assessed based on the hedonic price method (HPM) as a marginal cost in overall rental prices of rooms, estimated as a percentage of their current prices [39].

Putting people health and well-being at the centre implies a shift from the private perspective to the whole society one. Assuming a public viewpoint, energy and indoor air performances of buildings have several implications. In this research two impacts are identified - "Emissions" and "Health". The latter refers to health outcomes of indoor air; the former refers to the emissions of Particulate Matters (PM) caused by energy consumption, which have an impact on outdoor air. Health impacts of indoor air can be numerous, and their direct quantification based on specific influencing factors is currently an open research question. The "Health" impact considered in this paper refers to headache cases, whose risk factor (among others) was found in winter overheating [23]. Differently than "Energy" and "Losses", whose economic burden is on the private building manager only (i.e., internal impacts), "Emissions" and "Health", involve the whole society (i.e., external impacts), so their monetization requires a specific attention. Indeed, these impacts are accounting for costs burdening on the whole society in terms of i) monetary value of reducing harmful effect of air pollution in terms of PM emissions, ii) and healthcare costs of headaches, including direct and indirect costs as absenteeism from work, diagnostic investigations, hospitalization, outpatient health care, prophylactic medications and acute medications, paid out-of-pocket from people but also by government or insurance companies. For the former, the use of parametric values from literature is suggested [40], while in case of the latter the Cost of Illness approach (COI) is used, defining an average daily cost per capita [41].

To make the best interest of both the building manager and the society, all the identified economic impacts of building performance must be minimized (see column "Aim" in Table 2) by a potential project. The analytical approach to computation of daily impacts is reported in the followings.

"Energy" refers to the cost for energy carrier provision, which is related to the energy performance of the building (as assessed through EnI KPI). Monetization is based on the energy price.

$$Energy_{€} = \sum_j Cons_j \cdot PriceEn_{\,j} \; [€/\mathrm{room} \cdot day]$$

Where *Cons* is daily consumption of each energy carrier j in kWh/ (room · day), which equals EnI indicator (or indicators, if more than one energy carrier is involved); *PriceEn* is the energy price of each energy carrier j (VAT and taxes included) expressed in €/kWh.

"Losses" refers to the missed gain for sub-excellent indoor conditions, thus it is related to the indoor air performance of the building (as measured via PCH and SD indicators). Monetization is based on people WTP for improved indoor environmental condition in hotel rooms, which is assessed as the marginal cost of current rental prices of rooms (according to HPM) estimated as a percentage of their current prices [39].

$$Losses_{€} = s \cdot R \cdot Q_{-} \ [€/\mathrm{room} \cdot day]$$

Where *R* is the current daily rental price per room expressed in €/ (room · day); *s* is the percentage increase of currant rental price corresponding to guests' WTP for better indoor conditions [39]; Q_{-} is a dichotomic coefficient (it can be 0 or 1) indicating presence (1) or absence (0) of sub-excellent indoor quality. By default, it equals 1 (baseline). If a strategy that brings higher PCH and lower SD is introduced, Q_{-} under project scenario equals 0.

"Emissions" refers to PM emissions, which must be priorly quantified by multiplying the energy consumption per each energy carrier by the correspondent emission factor. Their monetization is performed by multiplying the estimated emissions (expressed in gPM) times a parametric cost of PM emissions [40].

$$Emissions_{€} = \sum_{j} Cons_j \cdot CoefPM_j \cdot CostPM \ [€/\mathrm{room} \cdot day]$$

Where *Cons* is daily consumption of each energy carrier j in kWh/ (room · day), which equals EnI indicator (or indicators, if more than one energy carrier is involved); *CoefPM* is the emission factor for each energy carrier j expressed in gPM/kWh; *CostPM* represents the cost of PM emissions in €/gPM, as defined by [40].

"Health", as DhOR(T) and OH before, was defined based on scientific knowledge on the correlation between indoor parameters and SBS occurrence. In particular, [23] found that SBS prevalence rates in winter increased as temperatures increased above 23°C and provided adjusted odds ratios (ORs) for the symptom prevalence increases for each 9 degree-hours above 23°C. Knowing this and assessing current prevalence of cases, extra cases of headache due to the risk factor of overheating in winter can be quantified. Their monetization is performed according to the COI approach, by multiplying cases times the cost of headache.

$$Health_{€} = P\,(RR - 1) \cdot Occ \cdot CostHead \;\; [€/\mathrm{room} \cdot day]$$

Where *P* is current daily prevalence of headache [23]; *RR* is the relative risk factor of overheating as was found in previous research [23]; *Occ* refers to the daily number of occupants exposed to the risk factor in room expressed in person/room; and *CostHead* is the daily cost of headache [41] expressed in €/(person · day).

RR was assumed equal to the OR provided by [23] for each 9 degree-hours > 23°C, as reported in the formula:

$$RR = OR^{\frac{D}{9}}$$

Where OR: (a-dimensional) Odd Ratio of the risk factor of overheating, assumed by [23]; *D* are daily degree-hours in room, which equals OH indicator.

2.2. Clustering

According to the methodology (section 2.1), the newly developed KPIs should support a building performance assessment that considers the quality of indoor air in respect to people health and well-being to be coupled with energy based KPIs towards healthier buildings. Interventions (e.g., new management strategy) could be then evaluated based on a set of criteria (i.e., impacts) that, if quantified in pre and post project scenarios enables a comprehensive (i.e., including energy and indoor air domains) evaluation on whether the project brought some benefits. An open question refers to which interventions should be then encouraged. In this sense, H2020 MOBISTYLE strategy is based on driving a behavioural change in buildings occupants, whose habits have a significant influence on energy consumptions, but also on people health and well-being. Indeed, the influence of occupants' behaviour on buildings performances is well recognized in literature, and an occupant-centric strategy for building management seems the most sustainable way forwards. In this sense, when health and well-being topics are concerned, the subjectivity in human response supports the idea that there should not be a “one-fit-all” solution to build a healthy space, but rather the adoption of occupant-centric solutions. However, this conflicts with the need for designing common guidelines for building managers. So, in this research, a tool to support the adoption of tailored actions is proposed for hotels by defining types of guests (i.e., clusters). KPIs and impacts are computed per cluster of guests to have tailored benchmark values for future assessment.

The clustering proposed in this research is based on a deterministic approach (i.e., using a predefined criteria) avoiding the use of personal data (e.g., sex, age, etc.). As in H2020 MOBISTYLE project, clusters are identified as the combination of two variables of occupancy, which are believed to influence occupants’ behaviour and habits (e.g., use of certain appliances, different comfort expectations, etc.) and, subsequently, energy consumptions and indoor air conditions associated to their stays. These variables are:

- Guest types. They can be single (S), couple (C), or family (F)
- Duration of the stay. It can be short (a), medium (b), or long (c)

According to the above-reported variables, guests (thus, the data gathered during their stays) can be grouped in nine clusters to perform the performance assessment. From a computational point of view, this means computing KPIs and impacts as daily averages, grouping the days associated to the same cluster type. To exclude the influence of the seasonality on results, only data from the same season (e.g., heating and non-heating season) should be used. As exemplification, results in terms of KPIs and impacts (section 3) per cluster of guests.

3. Results and discussion

In this section variables, indicators and impacts are exemplified on the Italian pilot of H2020 MOBISTYLE project.

3.1. Case study

Italian H2020 MOBISYLE pilot is represented by a residence hotel in renovated historical building in Turin. Heating and cooling are provided by a water-based climatization system, (i.e., fan-coils), where water is heated by one centralized gas boiler (also producing domestic hot water) in winter and refrigerated by a cooling machine in summer. The regulation is performed thanks to one thermostat per each apartment, where occupants can adjust the set-point of ± 3°C, influencing the speed of the fan-coil fans. Window switches enable the automatic deactivation of the heating/cooling system when any window of the apartment is open. Within H2020 MOBISTYLE project, a standing monitoring system was installed, including an energy meter per each apartment, smart plugs per each appliance and a datalogger collecting data on indoor air temperature, relative humidity and CO_2 concentration in the bedrooms. One apartment of 45 square meter was selected for this application.

3.2. Data collection

The dataset prepared to exemplify the methodology consists of parameters (according to section 2.1.1): energy consumption (kWh), indoor air temperature (°C), indoor air relative humidity (%), and CO_2 concentration (ppm). Related sensors are summarized in Table 3.

Table 3 – Sensors' specification for the data collected in the hotel room.

Parameter	Devise name	Range	Accuracy	Resolution	Frequency
Air temperature	SchneiderCO2, humidity and temp. Sensor KNX	0-40°C	±1°C	0.1°C	15 min
Relative Humidity	SchneiderCO2, humidity and temp. Sensor KNX	1-100%	±5%	0.1%	15 min
CO_2 concentration	SchneiderCO2, humidity and temp. Sensor KNX	300-9999ppm	300-1000 ppm: +/-120 ppm1000-2000 ppm: +/- 250	1 ppm	15 min

			ppm2000-5000 ppm: +/-300 ppm		
Electricity consumption	Zennio KES KNX Energy Saver	0.3A - 60A	±5%	10W	10 min

Energy consumption is referred only to electricity (including all electricity uses of the apartment), and it is recorded by a meter installed at the apartment level as cumulative kWh consumed over time, from which daily consumptions per room (i.e., EnI indicator) were computed by subtracting cumulative consumption every day at 00:00 to the one of the day before at the same hour. Indoor air related parameters were treated as hourly averages, computed starting from 15-min records, to be used as input for further computation of the metrics developed in this research. All the available data from the heating season 2018-2019 were used (from October 15th to April 15th, both included). In order to exemplify KPIs and impacts per cluster of guests (according to the approach reported in section 2.2) calendar days were also associated to a cluster type through a label (i.e., Sa, Sb, Sc, Ca, Cb, Cc, Fa, Fb, Fc) by analysing anonymous data provided by the hotel staff in terms of the two variables on which clustering is based: the number of guests per stay and the duration of the stay. The duration of the stay is classified according to the following assumptions: short stay (a) means until 5 days, medium stay (b) occurs if the stay is between 6 and 14 days, long stay (c) equals 15 days or more. Singles (S), couples (C), and families (F) occupation of the room was identified based on number of persons (respectively one, two, more than two).

The definition of other data and assumptions needed for the computation of all metrics was performed mostly based on standards and literature, avoiding the use of personal data. Assumptions refer to:

- Comfort ranges - for hOR(x), ShOR(x) computation
- Hours of occupation - for PCH, SD and OH computation.

In computing impacts, further data from literature or from the specific case study were also needed in terms of:

- Energy price - for “Energy” impact monetization
- PM emission factors for electricity - for “Emission” impact quantification
- PM costs - for “Emission” impact monetization
- Guests’ willingness-to-pay (WTP) for improved indoor quality and price per night - for “Losses” impact monetization
- Prevalence and Relative Risk of headaches, and occupants exposed to the risk - for “Health” impact quantification
- Cost Of Illness (COI) for headache - for “Health” impact monetization.

All data is summarized in Table 3.

Table 4 – Data used for the application to the Italian case study

Data	Value	Source
Comfort ranges	$T(I)_{lim,low}$ = 21°C $T(I)_{lim,up}$ = 25°C $T(II)_{lim,low}$ = 20°C $T(II)_{lim,up}$ = 25°C $T(III)_{lim,low}$ = 18°C $T(III)_{lim,up}$ = 25°C $RH(I)_{lim,low}$ = 30% $RH(I)_{lim,up}$ = 50% $RH(II)_{lim,low}$ = 25% $RH(II)_{lim,up}$ = 60% $RH(III)_{lim,low}$ = 20% $RH(III)_{lim,up}$ = 70% $CO_2(I)_{lim}$ = 750ppm $CO_2(II)_{lim}$ = 900ppm $CO_2(III)_{lim}$ = 1200ppm	Standard EN 16798-1:2019* [11]
Hours of occupation	before 9a.m. and after 7p.m., both included (Hotel Guest rooms).	Standard ISO 18523-1:2016 [42]
Energy price (electricity)	0.21 €/kWh	Case study specific
PM emission factor	0.0076 gPM/kWh	Case study specific
PM cost	0.10805 €/gPM	Copenhagen Economics [40]
Guests’ WTP	14% of current value	Buso et al. [39]
Price per night or room	100 €/day	Turin average
Prevalence (P) of headache	0.0304 **	Mendell et al. (2009) [23]
Relative Risk (RR) of headache	1.19	Mendell et al. (2009) [23]
Occupants exposed	1, 2 or 3 person/room for single, couple, family type, respectively.	Case study specific
COI for headache	1.8 €/ (person · day) ***	Linde et al. (2012) [41]

* With CO_2 concentration of outdoor air 400 ppm ** In this analysis, current daily prevalence (P) was assumed from [21] as 0.152 over a working week, consequently 0.0304 per day. *** Costs of headache are gathered from a study according to which in Europe the annual cost pro capita is equal to 1778 €, 648 € if reduced productivity at work is excluded (not applicable in this context), it means 1.8 € per day.

3.3. Variables, Indicators, and Impacts

Results in terms of computed variables, indicators and impacts from the filled areas of fig. 1 (i.e., innovative metrics) are presented in the followings, exemplifying the added value of the methodology and the main conclusions that the approach enables.

hOR(x) and ShOR(x) and DhOR(T) were calculated per each hour of the days of the computation period (heating season 2018-2019) and, thanks to the colour code defined in the methodology section (Table 1), mapped in carpet plots. The latter are reported in the following for an exemplificative month (i.e., November 2018).

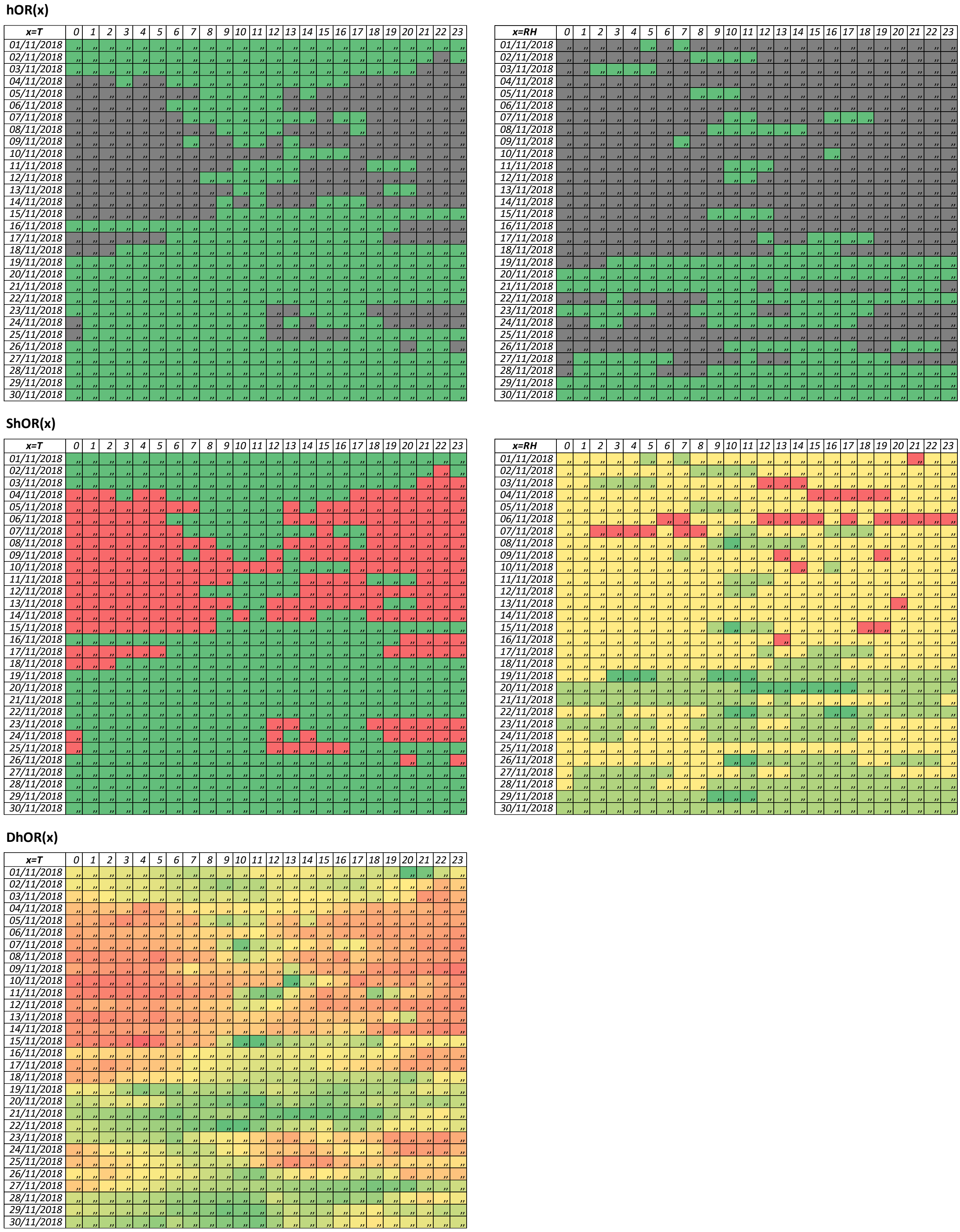
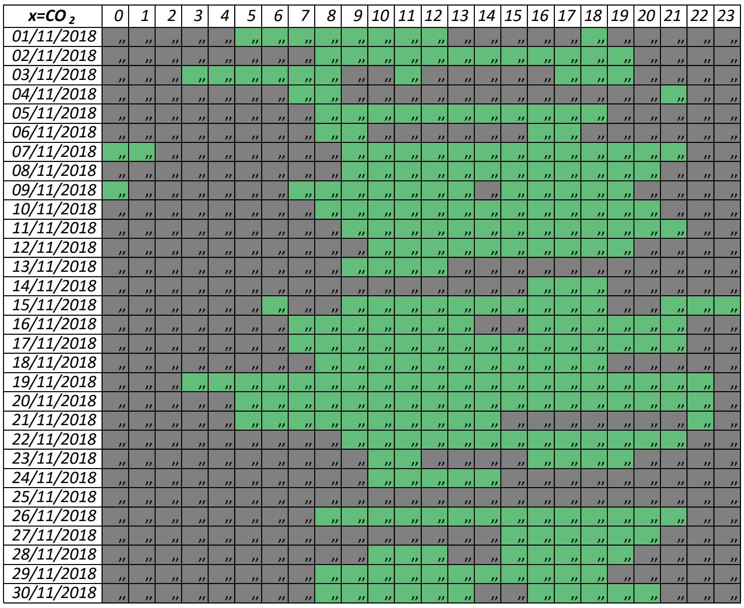


Figure 2 – Results from the variables computation in the hotel room for a reference month. Carpet plots for hOR(T) and hOR(RH) (top), ShOR(T) and ShOR(RH) (middle), and DhOR(T) (bottom). hOR(x) is hour outside range in terms of parameter x. ShOR(x) is severity of hour outside range in terms of parameter x. DhOR(T) is degree hours outside range in terms of parameter T.

By observing the graph related to hours outside range in terms of indoor air temperature (i.e., variable hOR(T), top-left of Figure 1), it is possible to see that they mostly occurred in the first half of the month and during night-time (grey hours in the carpet plot). This is true also for relative humidity (i.e., variable hOR(RH), top-right graph of Figure 2), which more often than temperature fell outside the pre-defined range (grey hours in the carpet plot). However, when temperature was outside the pre-defined range, severity variable for the same parameter (i.e., ShOR(T) variable, middle-left graph of Figure 2) resulted higher (and, according to colour code, red) than the severity variable in terms of relative humidity (measured as ShOR(RH) variable, middle-right graph of Figure 2) that occurred when relative humidity was outside the pre-defined range. This means that when indoor air temperature was not complaint with the pre-defined range, the non-compliance was more severe than what happened for relative humidity; the latter, even when it was not within the pre-defined range considered as adverse to people health and well-being, was not so far from it. It is also possible to observe that in those hours when high severity variable showed a severe dis-compliant in terms of temperature (red hours in the ShOR(T) carpet plot), there was a phenomenon of overheating. This is measured by DhOR(T) variable (bottom-left graph of Figure 2), which grows higher (and, according to colour code, turns into red shades) the more the indoor air temperature exceeds 23°C in a specific hour. This means that the distance from excellent ranges of indoor air temperature, as measured by the ShOR(T) variable, was towards too high temperature rather than to too low ones. Moreover, DhOR(T) variable observation added information on health and well-being concerns, not mapped by hOR(T) and ShOR(T); hours within pre-defined range (dark green hours in the hOR(T) carpet plot) and characterized by excellent indoor quality in terms of indoor air temperature (dark green hours in the ShOR(T) carpet plot), could still pose some issues in terms of headaches occurrence (yellow and orange hours in the DhO(T) carpet plot). Under the assumptions of this study, this happens for, e.g., indoor air temperature of 24°C.

The graph related to hours outside range in terms of indoor CO_2 concentration (i.e., hOR(CO_2) variable, Figure 3) shows that often this parameter was not-compliant with pre-defined range during nigh-time (grey hours in the carpet plot). This is consistent with the position of the sensors that, because of H2020 MOBISTYLE needs, were located in the bedrooms, where people are producing CO_2 overnight. Severity variable for indoor air in terms of CO_2 (i.e., ShOR(CO_2) variable) got smaller (turning from red to green) starting from the first hours of the morning, with slightly different patterns in different days. Since the room was always occupied (as reported by the hotel staff), this can mean that the ventilation strategy (i.e., windows opening, since there is not VMC) was not always the most effective in lowering the likelihood of SBS occurrence (which, according to literature, is correlated to ventilation rate and CO_2 concentration, as mentioned in introduction).

hOR(x)



ShOR(x)

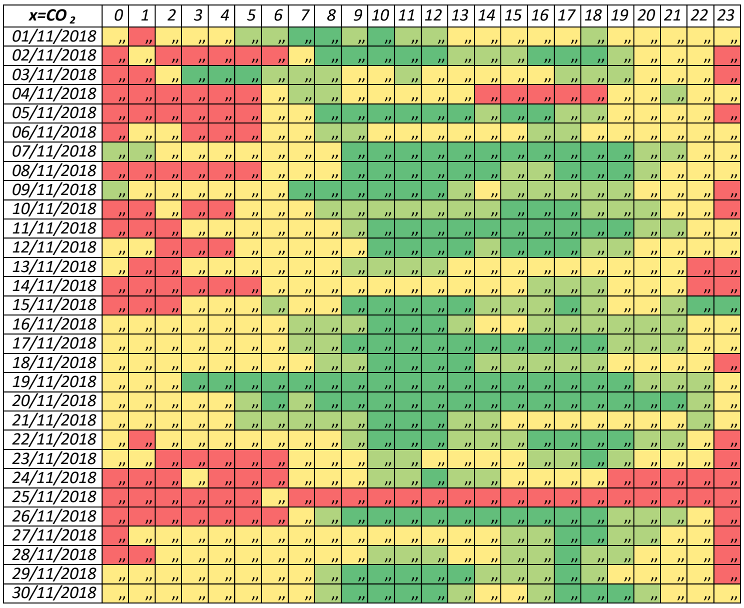


Figure 3 – Results from the variables computation in the hotel room for a reference month. Carpet plots for hOR(CO_2), and ShOR(CO_2) (bottom). hOR(CO_2) is hour outside range and ShOR(CO_2) is severity of hour outside range in terms of CO_2.

Indicators (PCH, SD and OH, in Figure 4) were computed per cluster of guests according to the approach reported in section 2.2. This means that they were firstly computed per each day of the computation period (heating season 2018-2019) and then averaged between days characterized by the same cluster label (i.e., Sa, Sb, Sc, Ca, Cb, Cc, Fa, Fb, Fc).

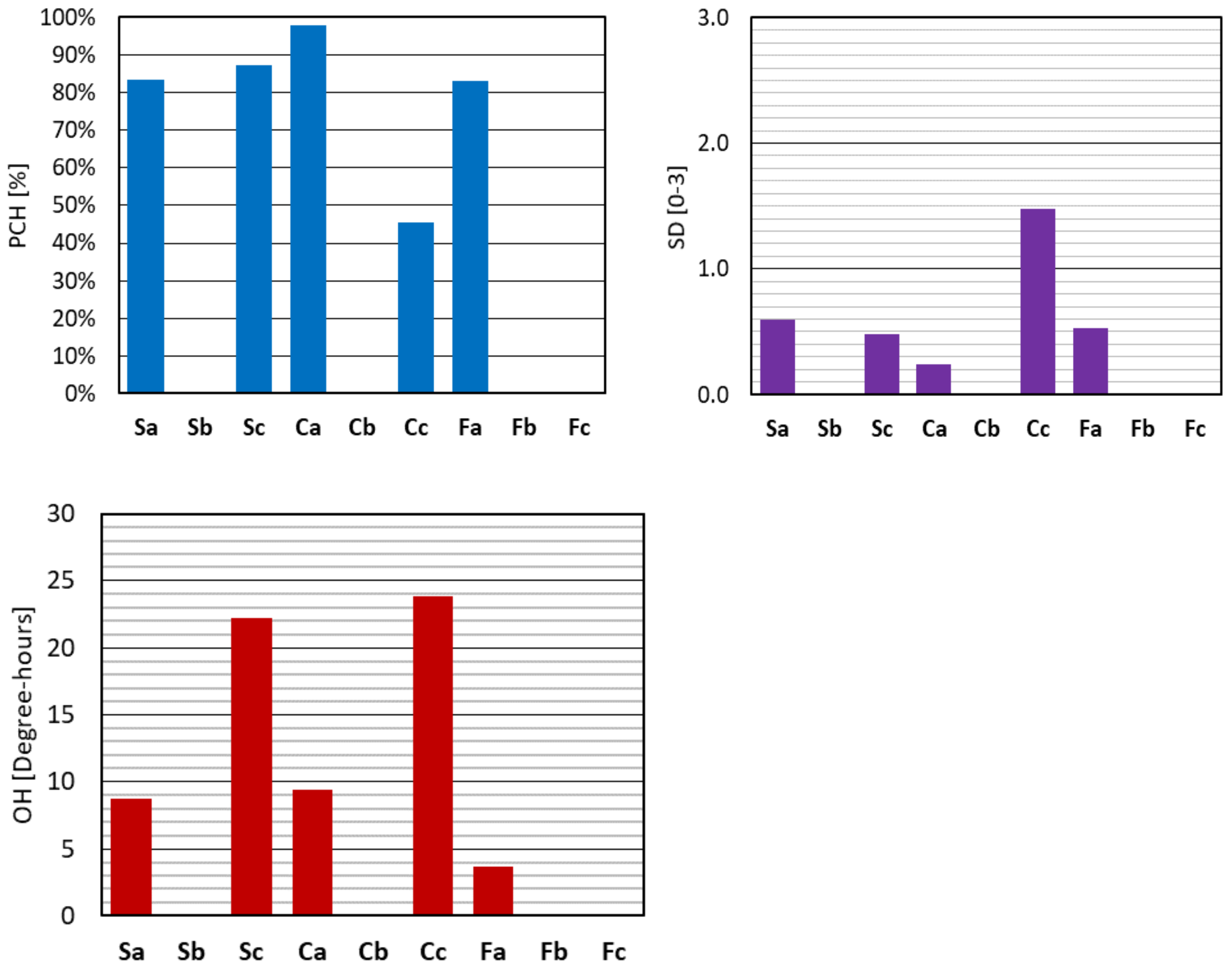


Figure 4 –Results of indicators per cluster. PCH is percentage of compliant hours. SD is severity of dis-compliant and OH is overheating hours. Labels of clusters are function of guest type (S single, C couple, F family) and duration of the stay (a short, b medium, c long).

From Figure 4, it is possible to see that the guests who had the best conditions in terms of all three parameters considered relevant in respect to human health and well-being were couples living in the hotel for short stays (i.e., cluster Ca). Indeed, their PCH indicator is the highest (PCH=98%), meaning that they spent almost all the occupied hours with all the three parameters within ranges defined as safe in regard to their health and well-being. SD indicator suggests that indoor conditions were on average not severe (i.e., SD=0.2). On the contrary, couples living in the hotel for more than 14 days (i.e., Cc) were those with the worst indoor conditions, spending less than 50% of time within range (i.e., PCH=46%), and with overall severe conditions (SD=1.5). A quite high OH indicator for this cluster suggests that the main issue was the long time spent with more than 23°C (i.e., overheating). OH indicator is high also for singles having long stays (i.e., Sc), despite they spent most of their time in complaint conditions (PCH=87%). This result underlines the value for including specific health related indicators in the performance evaluation, which allows to detect issues that otherwise would not be mapped.

Once current energy and indoor air related performances of the room per cluster of guests were assessed (in terms of PCH, SD and OH indicators), impacts of those performances were computed according to the equations reported in section 2.1.4. Figure 5 reports economic impacts (Y-axis) of current performance from private (left) and public (right) perspectives. They are reported as daily averages per cluster of guests (X-axis). This means that they were firstly computed per each day of the computation period (heating season 2018-2019) and then averaged between days characterized by the same cluster label (i.e., Sa, Sb, Sc, Ca, Cb, Cc, Fa, Fb, Fc).

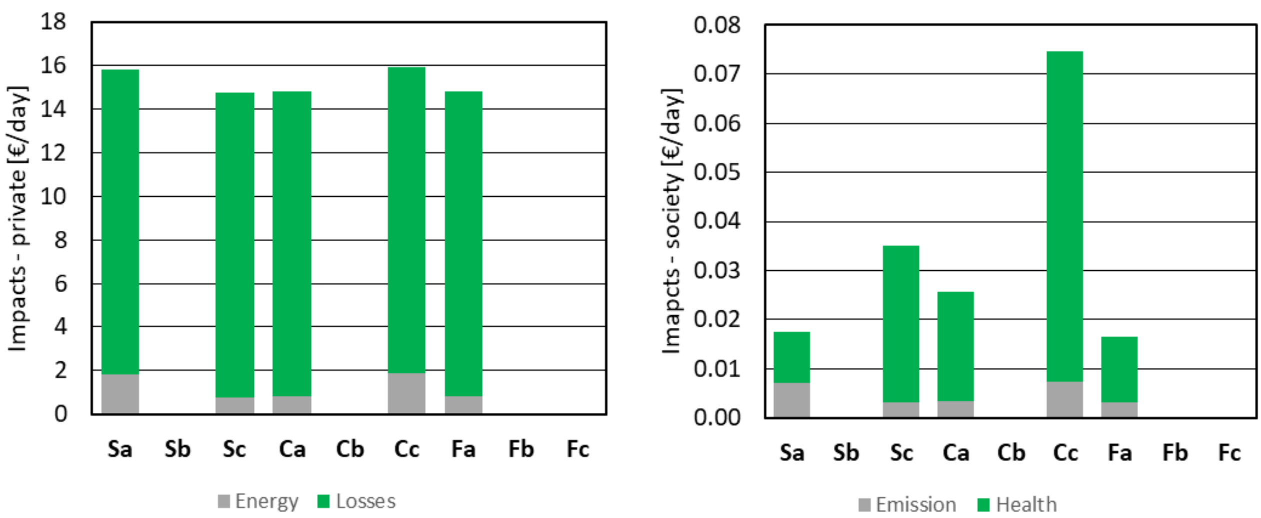


Figure 5 –Results of impacts per cluster: private (left) and society (right) perspective. Labels of clusters are function of guest type (S single, C couple, F family) and duration of the stay (a short, b medium, c long).

From Figure 5 it is possible to conclude that adding impacts related to indoor quality enabled to include a significant share (in green in Figure 5) of the overall economic impacts of building performance from both perspectives. This was possible thanks to the computation of the economic losses for the manager due to sub-excellent indoor air conditions ("Losses" impact), and of the costs for headache (caused by winter overheating) as burden to the whole society ("Health" impact).

4. Discussion

As mentioned in introduction, beside comfort-based indicators, there is the need for health-based ones to support the design of healthy buildings by taking into consideration impacts of indoor air conditions on human health and well-being. Despite some metrics used in literature are already directly (e.g., sick leaves) or indirectly (e.g., a lack in performance, possibly due to the incidence of non-reported SBS symptom compromising cognitive skills) descriptive of health-related concerns of indoor environment, a further step is still to be done. This consists, e.g., in promoting epidemiological studies that model the relationship between indoor parameters and diseases. Their incidence (as a new quantitative health indicator) would be forecasted by knowing indoor parameters status, thanks to newly developed concentration-response functions. However, literature is mostly focused on identifying parameters and health/well-being correlations. This paper takes advantage of this knowledge to define health and well-being driven metrics based on commonly collected parameters. The methodology is based on the definition of relevant parameters, variables, and indicators (or KPIs). Their definition is in accordance with knowledge from literature on the implications of IEQ on people's health and well-being, and it can boost building management practices more attentive to these topics. Since most of the reference values embedded in the definition of the metrics are in line with the relevant Standards (namely EN 16798-1 [11]), their adoption is not an obstacle to the regular practices. A step forwards is done by identifying economic impacts of the building performances that the set of metrics (energy and indoor air related) describe, which can be monetized and aggregated into a single metric of the overall performance of the building from a multi-domain (energy and indoor air) perspective.

Speaking about the individual parameters, indoor air temperature, relative humidity and CO_2 concentration were selected. This is not fully in line with the findings of [12]. The authors identified the parameters that are mostly used to assess IEQ in offices and hotels by Green Building certification schemes. For Thermal environment, Predicted Mean Vote (PMV) is the most common index, followed by room air relative humidity and room operative temperature. Since the measurement of operative temperature is more complex, in this research, the adoption of indoor air temperature instead aims at guaranteeing the practicality of a continuous measuring and logging of data, for a running assessment of the building performances. PMV is not adopted, since the model behind its computation is bounded to certain building characteristics (i.e., fully mechanical controlled building), which would reduce the scalability of the evaluation model. Regarding IAQ, CO_2 concentration is between the four most used parameters, overcome only by ventilation rate [12]. Since the measurement of ventilation rate is non-trivial, CO_2 is selected as main variable in this research, supported by the fundings on its good capability to predict IAQ in occupied spaces and its positive correlation to other pollutants concentration [21]. In a recent study aiming at studying IEQ in hotels [43] the same parameters are collected in hotel rooms. The same is observed in two studies addressed to offices and hotels [44] [45], aiming at developing an user-friendly IEQ calculators and a IEQ- based rating schema, respectively.

The strength of this research is in the attempt of combining different domain of evaluation, through the identified set of indicators and impacts. Referring to the former, it is possible to observe that, despite the evaluation of buildings performance and its retrofit alternatives is a topic widely covered in literature, studies focusing on the identification of appropriate metrics for their evaluation according to an holistic approach remain limited. A recent literature review [46] on KPIs for holistic evaluation of building performances identified fifty-two indicators, which were shortlisted based on the opinion of experts to nineteen. Interestingly, the exclusion of some metrics was mostly due to impracticality of their computation for excess of resources or because they were considered not easy to understand. In the present paper, only metrics based on monitored parameters that are commonly available or easy to collect (i.e., well-established sensor types and affordable prices) were identified. Moreover, they are translated into units which are either percentages, scores, or euros, which are very easy to understand and communicate, also thanks to colour codes.

By selecting possible economic impacts of a building performance related to energy and indoor air, a broader evaluation schema is provided. Some examples of evaluation schema were found in literature. In [45] a rating schema aiming at assessing the overall IEQ performance in offices and hotels is presented, supporting deep energy renovation aware of their IEQ implications. Twelve parameters were identified, covering al the dimensions of IEQ. Based on their measurements (according to a detailed protocol) before and after a deep renovation, a performance score is assigned to each parameter. Then, a score is inferred per each dimension (thermal, indoor air, lighting and acoustic), which are finally translated into an overall IEQ score. Interestingly, the worst parameter and dimension are dictating the scores for the single dimension and the overall IEQ, respectively, refusing any compensation mechanism. On the contrary, in [47] a weighting system is introduced as part of the multi-criteria model that has been proposed to measure the overall IEQ performance for office spaces. In this research, differently than in the cited literature, the evaluation methodology aims at combining the performances related to the indoor environment to the energy ones, encouraging their combined control. Moreover, the aggregation strategy is only based on the monetization of the indicators, implying that their relative importance is connected to their economic implications from both a private and public standpoint. Regarding indoor environment domain only, the KPIs presented in this research embrace a compensative approach, since acceptable results of complaint hours (PCH indicator) and severity of dis-compliance (SD indicator) can still be reached if only one of the three parameters is performing badly. However, this can be adjusted in future by tailoring the weights attributed to them, once more knowledge will be gained on the relative importance of the parameters in regard to people health and well-being.

5. Conclusions

In this paper a multi-step assessment procedure embedding in buildings assessment health and well-being related metrics is elaborated in respect to non-residential buildings, more specifically hotels. The methodology is exemplified starting from monitored data gathered during a full heating season in one hotel room from the Italian pilot of H2020 MOBISTYLE project.

The introduction of specific health related indicators in the performance evaluation allowed to detect issues that otherwise would not be mapped (e.g., the risk of headache due to winter overheating). Also, adding impacts related to indoor quality enabled to account for a significant share of the overall economic impacts of building performance from both public and private perspectives. Moreover, since all the economic impacts are in the same unit of measurement, namely euro, they could be summed to obtain a single monetary metric (i.e., "€" in Figure 1) of overall economic performance of the building system in terms of its impact on energy costs, financial losses for sub-excellent indoor conditions, emissions costs and health related (i.e., headache) cost. Any future strategy whose introduction will be able to reduce "€" value can be considered as producing economic benefits, quantified as the difference between "€" before and after project introduction. The whole methodology is based on data coming from energy meter and probes for indoor air temperature, indoor relative humidity, and indoor CO_2 concentration. The three selected parameters can be collected in indoor spaces through a single monitoring device, which is an easy to install datalogger, widely available in the market and with a level of reliability of a professional meter. This circumstance enables the applicability of the methodology in building management practices with a small effort in the preparation of the hardware infrastructure.

Speaking about limitations and future improvement, it is important to underline that, in order to make the methodology replicable and scalable, the relevant parameters were lowered down to the most commonly collected. However, while pursuing healthy indoor spaces, certain pollutants (e.g., VOC) cannot be neglected, and they must be included in future studies. Even if there are not yet robust models in literature that enables their use in predicting health issues, the technologies for their continuous monitoring are evolving (i.e., so-called low-cost air quality sensors, LCAQS), and multi sensor devices will be more and more deployed. Sticking to the parameters treated in this research, the methodology has space for further development. For example, if PCH and SD indicators are integrated in building management services, weighting factors α involved in their computation could be customized. Moreover, impacts could be enlarged, deploying other models from literature. However, the applicability of these models outside the context where they were initially developed is an open issue, which also affects this research. Those models coming from meta-analysis of multiple experimental results should be prioritize. In this paper, the potentiality for their introduction in building management practices was intended to be showed. Between the impacts, "Losses" seems particularly promising: currently its quantification is based on a dichotomic variable for presence and absence of excellent indoor conditions. A more complex function relating indoor conditions to guests' WTP could be elaborated by studying guests' preferences.

Concerning the application to the Italian pilot of H2020 MOBISTYLE project, it enabled to analyse the building performance from a multi-domain (energy and indoor air) and multi-perspective (private and public) standpoint. However, the pilot configuration did not allow to include all the energy consumptions for the building, possibly underestimating the contribution of "Energy" and "Emissions" impacts on the results. The methodological limitations mentioned above are affecting this application as well, including the scarce knowledge of guests' subjective preferences on indoor air conditions. Indeed, guests' WTP for improved IEQ ("Losses" impact) refer to all the IEQ domains:

studies (including subjective parameters) are needed to define the weights of the components of IEQ on the overall perceived comfort and well-being and, thus, on people willingness to pay for them.

To summarize, the intent was to exemplify how the methodology, built on top of energy and indoor air related monitored data, can expand the traditional energy-based performance assessment for building management to the indoor air domain and to energy and indoor air related economic impacts, with implication on results in terms of overall economic performance of the building from both a private and public perspective.

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