COST Action CA16114 RESTORE: REthinking Sustainability TOwards a Regenerative Economy,
Working Group Four Publication: Rethinking Technology

RESTORE
REthinking Sustainability TOwards a Regenerative Economy

Regenerative technologies for the indoor environment

Inspirational guidelines for practitioners

EDITORS
Roberto Lollini, Wilmer Pasut

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EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

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RESTORE Working Group Four Report: Regenerative technologies for the indoor environment

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EXECUTIVE SUMMARY

Proper technology solution-sets can enable a regenerative indoor environment for building users and for the planet, thereby ensuring occupant wellbeing and health. Several aspects are considered for high indoor environmental quality, such as hygro-thermal comfort, visual comfort, indoor soundscape, indoor air quality and a pleasant ambiance. Regenerative indoor environmental quality must be achieved, through the minimization of environmental and social impacts linked to the solutions, while making optimal use of resources throughout the entire set of life cycles.

Key technologies can promote a paradigmatic shift in building design from "less bad" to "more regenerative". However, proper technologies need a dedicated evaluation framework for aware selection within a comprehensive decision-making process.

The activities of Working Group Four of the COST Action RESTORE were undertaken with the aim of defining the aspects that determine a regenerative indoor environment, so that all the technologies and their characteristics that provide this "regenerativeness" may be defined. Practitioners can approach aware design of indoor regenerative environments with examples of solution-sets within the building domain and case studies.

Regenerative design is built on the awareness that humans and the built environment exist together within natural systems. As such, Regenerative Design is aimed at reversing the damage that has been done, restoring ecosystems, so that they will thrive and evolve. As regards the design of spaces, regenerative design places occupant wellbeing centre stage. Here, the salutogenic focus is on making wellbeing part of the regenerative paradigm, rather than the reductionist approach of sustainable design that targets the absence of ill health. The term salutogenesis, coined by Aaron Antonovsky, means 'generation of health'. The approach we used towards preparing a list of KPIs consisted neither of nullifying nor of erasing the regulatory requirements. Instead, it was intended as a step towards the achievement of a better indoor environment and reconnection with natural elements. Upon these premises, the indicators identified in the state of the art underwent a filtering process, aiming at a number of KPIs ≈ 10, to be delivered as an additional and useful tool for helping the designer to develop regenerative buildings. For each KPI, a regenerative threshold is proposed, as shown in following table. As may be observed, besides the objective parameters that may be monitored with specific instrumentation, subjective ones are also introduced, i.e. the percentage of satisfied people assessed by means of POE survey questionnaires.

The transfer of technologies and techniques and their acceptance have to be based on sound knowledge of a regional culture. It must be recognized that the existing building stock forms an essential aspect of regional diversity and culture. A European approach is based on strong public policies, the importance of public service and active state intervention, especially in the realms of the built environment, 'green' issues and cultural heritage.

Climate is a defining variable that influences culture, buildings design, and 'human behaviour. [Nicol and Humphreys 2002; Zhang et al., 2017; Luo et al., 2016; Rupp, Vásquez, and Lamberts 2015]. There are several ways that people are affected by the climate, which are in turn related to either adapting or responding to the indoor climate.

Thermal comfort and indoor climate satisfaction are the results of a balancing process between the physical environment and subjective comfort expectations. Reactions and behaviour are based on experience. Thus, individual requirements and occupant satisfaction are "highly negotiable socio-cultural constructs" [Luo et al., 2016; Chappells and Shove 2005].

A Post-Occupancy Evaluation (POE) is necessary for a practical evaluation of the quality of the indoor environment. Among many other definitions in the scientific literature, POE has been characterized as "… the process of evaluating buildings in a systematic and rigorous manner after they have been built and occupied for some time." [Preiser, 1995].

Data collection, evaluation and feedback are the cornerstones of continuous improvement in the supply of buildings. A robust data-collection procedure is an intrinsic part of good building briefing and design. POE is a way to obtain this information during the life cycle of a building and is often used as a generic term that can include both: a review of the process delivery of a project; and, an evaluation of the technical and functional performance of the building during the time of its occupancy. Other than driving the operation of the building and its related systems, the information from data collection, evaluation and feedback can also be transferred to future projects.

Final list of KPIs and proposed values

Environmental aspect	Sub-aspect	KPI	Regenerative values
Air Quality Environment	*Contaminants*	Formaldehyde	≤ 0.1 mg m^{-3} [30 min]
	Outdoor/Indoor	Particulate matter: PM_{10} $PM_{2.5}$	< 150 µg m^{-3} [24h] < 12 µg m^{-3} [1yr]
	Occupant satisfaction	% satisfied people	80 %*
Hygro-Thermal Environment	*Temperature/ humidity/air speed*	Implementation of ASHRAE 55	ASHRAE 55 + evaluation of air movement
	Occupant satisfaction	% satisfied people	80 % *
Visual Environment	*Daylight*	Useful Daylight Illuminance	300 – 3000 lux
	Circadian Rhythms	Equivalent Melanopic Lux	≥ 200 (9am-1pm) **
	Occupant satisfaction	% satisfied people	80 % *
Acoustic Environment	*Background noise level*	Noise criteria	≤ 30 / ≤ 40 ***
	Occupant satisfaction	% satisfied people	80 % *
Human Nature Environment	*Right to light*	% with windows access to daylight	100 % of inhabitants
	Connectivity to Nature (Biophilia)	Intentional interior design interventions that bridge the gap between natural and built environments.	1. Biophilic Design Workshop held prior to design. 2. Biophilic Interventions incorporated: 7/14 Biophilic Patterns [Browning et al. 2014]. 3. POE *Connectivity with Nature* satisfaction.

* response rate representing at least one quarter of the total number of building/indoor environment users. Although a value of 100% is desirable, and in some cases like hygro-thermal comfort is achievable with the use of personal comfort systems [Pasut et al. 2015], we are aware that there will always be a percentage of people that despite all efforts may never be satisfied. For this reason, we aim at a value that is 80% or higher.

** for 75 % or more workstations.

*** enclosed / open offices.

POE can serve several purposes, including the following:

Short-term benefits

- Identification of building-related problems and definition of possible solutions;
- Response to user needs;
- Improvement of space utilization, based on feedback from users;
- Understanding the implications of changes within buildings (e.g., budget cuts, working context);
- Informed decision-making.

Medium-term benefits

- Built-in capacity for the adaptation of buildings to organizational change and growth;
- Finding new uses for buildings;
- Designer accountability for building performance.

Long-term benefits

- Long-term improvements in building performance;
- Improvement in design process quality;
- Strategic review.

Technology solution-sets that enable the design of the regenerative indoor environment will first of all need to implement specific functions and to ensure proper operational performance. A specific framework for the collection of such solution-sets has been created. The framework is a means of establishing the links between the environmental aspects, their sub-aspects, and the functions upon which the performance of the building systems and components depend, in order to achieve the goals, and the related technologies that can be applied. The table that appears below provides an overview of these links between environmental aspects and sub-aspects and the functions of the building systems and their components. The analysis has mainly been focused on technologies suitable for office buildings and five main environmental aspects. However, the way in which the framework is designed also means that researchers and practitioners can implement solutions-sets for other building types (e.g., residential and commercial or educational buildings) and/or increase the number and the typology of environmental aspects under consideration. The five environmental aspects (i.e. indoor air quality, hygro-thermal environment, visual environment, acoustic environment, human values) in our analysis will be described in the various chapters of the booklet. Within the indoor air quality aspect, sub-aspects related to contaminant concentrations, outdoor/indoor interaction, and occupant satisfaction have all been analyzed in detail. The related functions of the building, its sub-systems and components that fulfil the performance requirements are as follows: the capacity either to remove or to absorb pollutants; the capacity to change the air; and, the capacity to control the concentration of pollutants and contaminants. The information on technologies affecting the hygro-thermal environment aspects, the visual environment, and the acoustic environment were collected by focusing both on the objective and the subjective factors. The objective factors under consideration are air temperature, relative humidity and air speed for the hygro-thermal environment, the daylight availability for the visual environment, and the background noise levels for the acoustic environment. The subjective factors are, instead, always related to occupant satisfaction levels. The following functions of the building are needed to achieve the environmental goal: the hygro-thermal environment can be controlled by means of active and passive strategies; the visual environment can be controlled by either blocking solar radiation or facilitating its entry into the building. Finally, the acoustic environment can be controlled by means of two concurrent strategies: prevention and absorption of sound and noise.

The relation between environmental aspect, performance sub-aspects and building functions

Environmental aspect	Sub-aspect	Function
Indoor air quality	Contaminants	Remove/absorb pollutants Change air Control
	Outdoor/Indoor	
	Occupant satisfaction levels	
Hygro - thermal Environment	Temperature/humidity/air speed	Passive/active
	Occupant satisfaction levels	
Visual Environment	Daylight	Allow/block light and sun
	Occupant satisfaction levels	
Acoustic Environment	Background noise level	Prevent noise Absorb noise
	Occupant satisfaction levels	
Human Values	External view and Right to light	Allow view and light Include natural elements within the space
	Biophilia	

The last environmental aspect that has been analyzed is the one related to human values. Among the large amount of human values to be integrated into building design, we have selected the two with the closest relation to regenerative design principles: external view and right to light, enabled by means of the presence of a view towards the outside and natural light within indoor spaces, and biophilia, enabled by the inclusion of natural elements, such as plants, within the space.

The performance of these technologies must be evaluated during their life cycle, taking into account all the possible impacts. Although a mature concept, LCA is gaining ground, because it can be used to quantify the environmental impacts of design choices that span the entire life of the project. In the past, LCA was used to compare products and building sets, which provided some indication of how to progress with decision making, but provided no data on the long-term impacts resulting from construction operations.

There is also a wide-ranging life cycle thinking method which fairly considers all the environmental, economic, and social topics that is known as Life Cycle Sustainability Assessment (LCSA]. The LCSA is formally expressed with the following equation [Kloepffer, 2008; Matthias et al., 2010]:

$$LCSA = LCA + S\text{-}LCA + LCC$$

while LCA, S-LCA, and LCC can each be independently used. When applying the LCSA for a product, an equivalent system boundary must be used in all the three assessment tools, to avoid re-calculation [Curran, 2015] [Whitehead et al., 2015]. Clarification and translation of the results of the social impact for a product or a process into numerical values is no simple job. Agreement on this subject is therefore never easy and the proposed solutions are often inadequate [Whitehead et al., 2015].

Whole Building Life Cycle Assessment (WBLCA) has proven to be a complex exercise practiced by experts [Giesekam, Barrett, and Taylor, 2016]. Even though it has been incorporated into Green Building Rating Systems (GBRS), it is only in recent years that standardized methodologies have become accessible for building designers. The available methodologies are diverse and use a variety of international standards as their primary references. These variations imply differences in both goals and scope, particularly in relation to the description of the functional or reference units and system boundaries.

The varied approaches to WBLCA that are available in different GBRS for the evaluation of embodied carbon are a barrier for precise comparisons between buildings assessed with different tools, and likewise for the development of baselines to drive estimated reductions of environmental impact [O'Connor, 2014]. A standardized WBLCA methodology must be established for the building industry using simplified tools, in order to continue making advances with the holistic environmental assessment in buildings, including more robust databases and a large body of knowledge.

In conclusion, nature-built environment-humans are part of the same system (SEVA vision, compared to EGO and ECO, as reported in RESTORE WG1 booklet) and the key for defining optimal interactions is an interdisciplinary approach including building physics, cognitive science, sociology, medicine, environmental science, and economics. Such an interdisciplinary approach will help find well-balanced solution-sets for technologies that, properly applied, can serve to define regenerative indoor environments. A regenerative environment that will both restore and improve the natural environment (and humans likewise), as perfectly integrated within a built environment (building and surrounding), by enhancing the quality of life for biotic (living) and abiotic (chemical) elements.

Building smartness increases awareness and the transformation of collected data into useful information can support further investments to transform existing building stocks.

While the textbook definition of a regenerative indoor environment is in terms of IEQ and human values, there are some technical aspects to be considered such as statics, fire safety engineering, and architectural quality, which can also affect both building durability and resilience.

1 INTRODUCTION

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1.1 OVERALL APPROACH AND METHODS

Proper technology solution-sets can enable a regenerative indoor environment for building users and for the planet, thereby ensuring occupant wellbeing and health. Several aspects are considered for high indoor environmental quality, such as hygro-thermal comfort, visual comfort, indoor soundscape, indoor air quality, and a pleasant ambiance. Regenerative indoor environmental quality must be achieved, through the minimization of environmental and social impacts linked to the solutions, while making optimal use of resources throughout the entire set of life cycles.

Key technologies can promote a paradigmatic shift in building design from “less bad” to “more regenerative”. However, proper technologies need a dedicated evaluation framework for aware selection within a comprehensive decision-making process.
The activities of Working Group Four of the COST Action RESTORE were undertaken with the aim of defining the aspects that determine a regenerative indoor environment, so that all the technologies and their characteristics that provide this “regenerativeness” may be defined.
The present guidelines are intended for practitioners, so that they can approach aware design of indoor regenerative environments with examples of solution-sets within the building domain and case studies. The structure of the activities within the Working Group reflects the way in which these guidelines were conceived. It is an inspirational journey through the various elements that define a restorative indoor environment, its nuances, the much-needed evaluation tool, and a robust set of examples, which will lay the foundation for a new inspiring vision for designers and practitioners.

On this inspirational journey, we seek to provide a finite set of Key Performance Indicators (KPIs) that designers may use as a set of goals for the definition of indoor environments and their assessment. Furthermore, we will discuss the nuances associated with the targets of such goals and their consequences, due to different cultural habits, among users. Our cultural backgrounds may strongly influence our preferences with regard to indoor environmental parameters, which a designer must always keep in mind.
We have worked on the definition of technology solution-sets, so that they can foster a regenerative indoor environment (for people in the building). Solution sets that will be resilient against the contextual dynamics, finding a balance between positive effects on the indoor environment and the use of natural sources (circular exchange with the natural sources). The technology must guarantee reliable, robust and functional buildings, and aesthetics (enlivening happy and healthy people in different contexts) with positive environmental and social impacts. The question of “what amount of resources will be required for a regenerative indoor environment?” must be given a clear answer that has to be satisfactory from the perspective of the circular economy.

Among others, we defined a structured framework with some exemplary solution-sets to be further enhanced with the most interesting hard and soft technology that is contributing to regenerative indoor environments within different contexts.

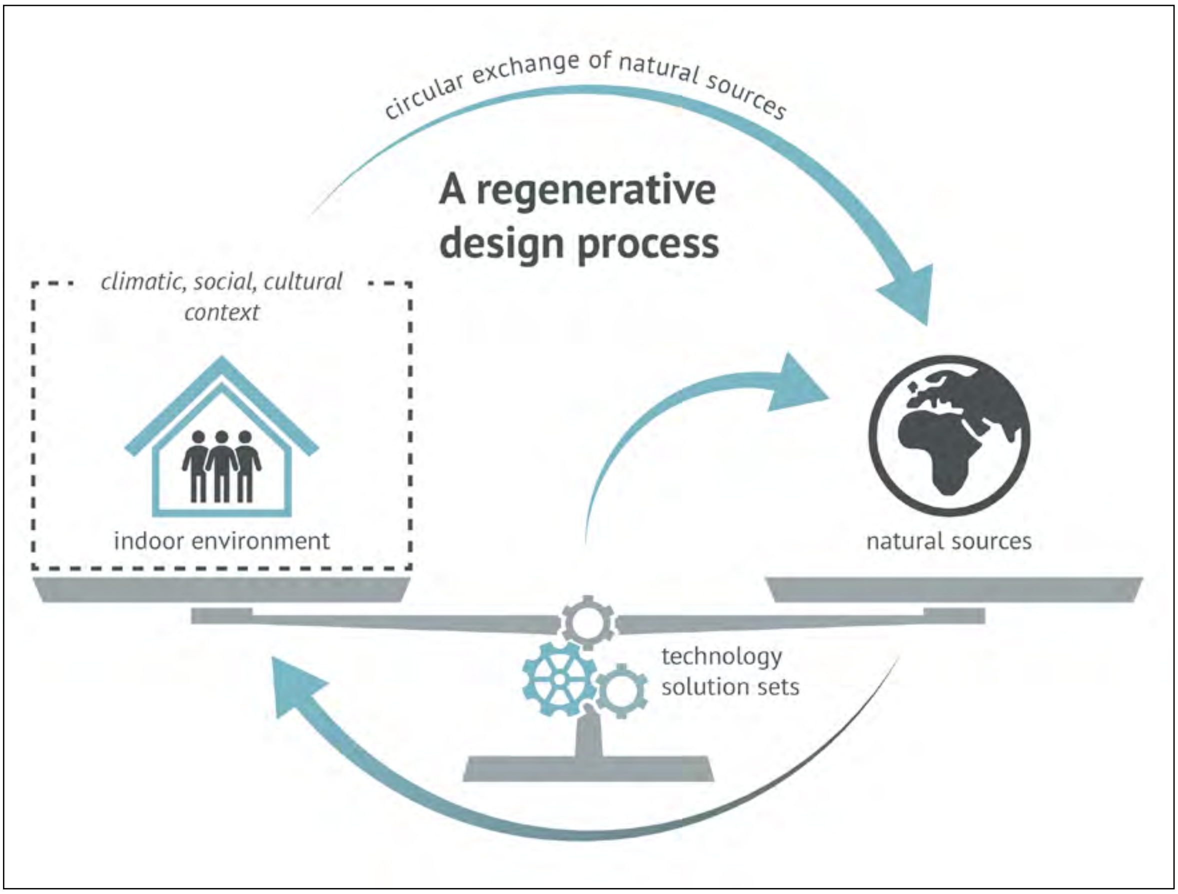

Figure 1. A circular exchange of natural sources from earth to the built environment is balanced thanks to proper technology solution-sets that enables a regenerative indoor environment, resilient against the context dynamics (Amy Segata, EURAC Research)

The RESTORE working-group activities around the topic of regenerative technologies are organized into six thematic areas with strong correlations between each one (Figure 2). These areas will be covered in Chapters 3 to 8 and may be summarized as follows:

a) "Technology-related parameters that make an indoor environment regenerative"
Focusing on the office building typology will narrow the scope for a concrete approach, although the same parameters may be extended to other building typologies. A set of KPIs are defined (including human perspective/perception: satisfaction) for the following areas:

- Indoor air quality
- Temperature, Humidity and Air velocity
- Visual environment
- Acoustic environment

Added to these, some others were in the area of human values

- External view and right to light
- Biophilia

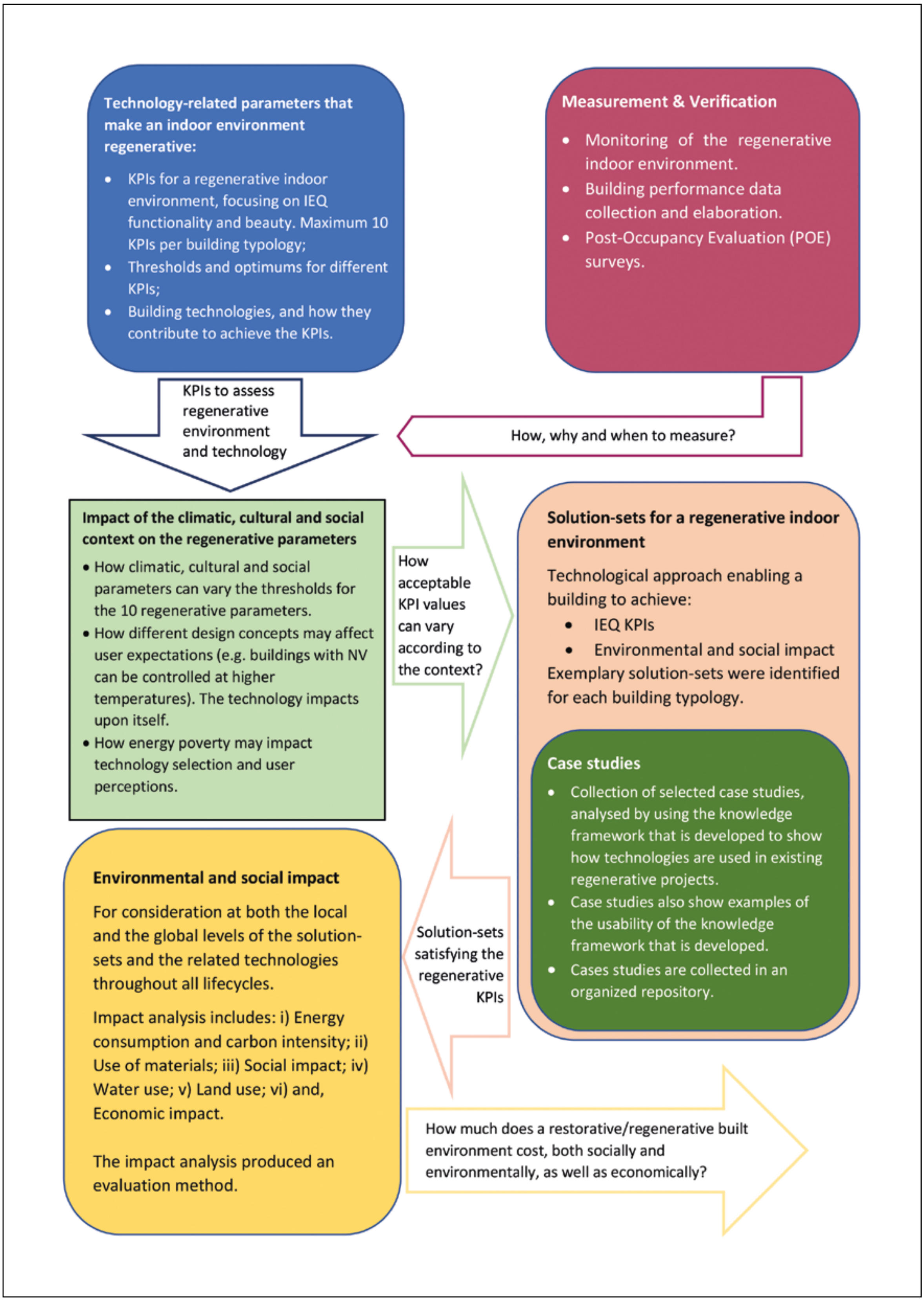

Figure 2. Overall work organization

b) "Impact of the climatic, cultural and social context on the regenerative parameters"
Focusing on the influence of the outdoor environment and both cultural and social contexts on indoor parameters and user expectations for a regenerative environment. Looking at the role that technology can play in guaranteeing a regenerative environment that can have a different meaning (varied KPI thresholds), based on cultural, social and climatic contexts.

c) "Solution-sets for a regenerative indoor environment"
Focusing on the definition of a knowledge framework: parameters (KPIs) - functions - building sub-systems (e.g., envelope, HVAC) and technologies scaled up to products. Specific solution-sets may be developed and further defined within this framework.

d) "Environmental and social impact"
Focusing on what the social/environmental costs will be, in order to achieve a regenerative built environment, and focusing on the three (LCA, Ecological Footprint, Urban Metabolism) assessment methods that the scientific community currently applies.

e) "Measurement & Verification"
Focusing on procedures and instruments to evaluate/monitor indoor environments and technologies, and protocols for collecting quantitative and qualitative data. In particular:
- Systematization of POE methods, protocols and tools;
- Subjective survey questionnaires for the assessment of environmental quality and occupant attitudes: techniques and methods of administering the questionnaires;
- Qualitative methods.

f) "Case studies"
Focusing on a fact-sheet template including KPIs, and on the definition of a case-study repository based on Google maps with the following features:
- Filtering depending on the types of technologies and KPIs currently in use;
- Factsheet pop-up activated by clicking on map icons.

1.2 DEFINITION OF RENOVATION TECHNOLOGY

In WG4, the term technology is used to refer to all those passive (insulation, thermal mass, etc.) and active (heating system, ventilation, fans, etc.) solutions that have an impact on the indoor environmental quality, as perceived by the users. The list of technologies may include, beside the technology itself (hardware side), the control logics (software side).
Furthermore, IEQ encompasses at least thermal comfort, visual comfort, acoustics, and air quality, so all four must be given consideration when evaluating what will or will not constitute a technology. For example: painting material, carpets, and furniture may all contribute to the indoor air quality, and will therefore be evaluated as technologies in this WG.

1.3 IDENTIFICATION OF THE BUILDING TYPOLOGIES

As a first step, the main building typologies for analysis were identified, in order to outline a common framework for the building stock. From this perspective, the Commercial Buildings Energy Efficiency Consumption Survey (CBECS)[1] of the U.S. Energy Information Administration (EIA) was used as a reference. A clear classification of building typologies may in fact be found in this document, based on their principal activities and functions. Aside from the main categories, specific sub-categories are specified, so as to ensure the quality of the information.
The main reason for this preliminary classification, insofar as a common definition may be considered, is to be able to define: (i) the functions and tasks that are performed; and, (ii) the occupants performing those functions and tasks, so as to clarify the objectives and goals to be pursued for each type of building (Figure 3).

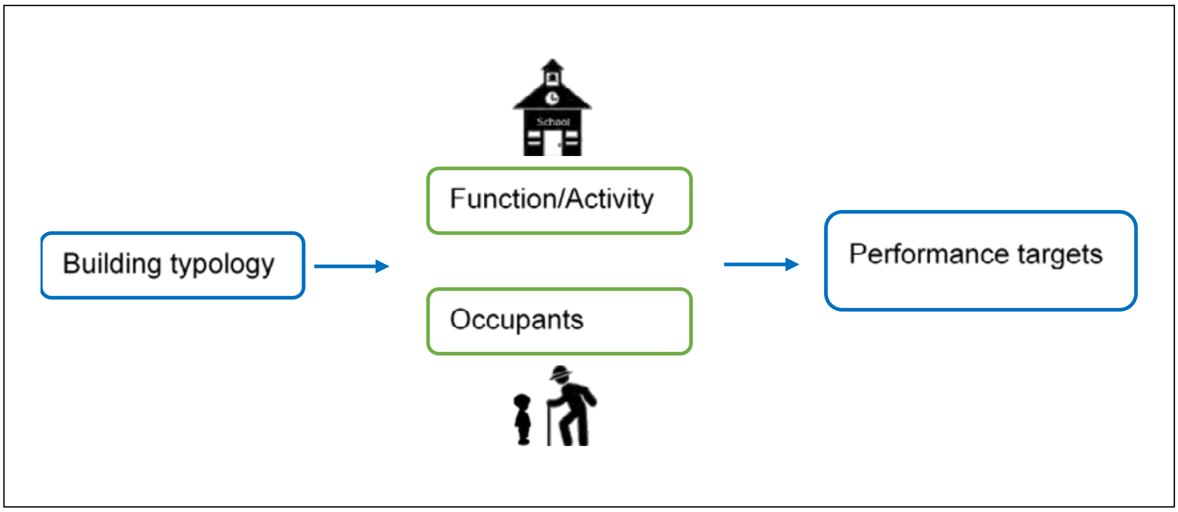

Figure 3. Drivers for the building-typology analysis

Among all the categories listed in the CBECS document, those chosen for this analysis are listed below in Table 1.

Table 1. Adapted from the Commercial Buildings Energy Efficiency Consumption Survey (CBECS). Building types selected for the investigation and their definitions

Building type	Definition
Education	Buildings used for academic and/or technical classroom instruction, such as elementary, middle, and high schools, and classroom buildings on college or university campuses. Buildings on educational campuses, the main use of which is not listed as a classroom, are included under the category relating to their use. For example, administration buildings are listed under “Office,” dormitories under “Lodging,” and libraries under “Public Assembly”.
Office	Buildings used for general office space, professional offices, or administrative offices. Medical offices are included here, unless they contain diagnostic medical equipment (if so, they are categorized as outpatient health-care buildings).
Lodging	Buildings used to offer multiple accommodation for short-term and/or long-term residents, including skilled nursing staff, and other residential care buildings.
Retail	Buildings used for the sale and the display of goods other than food. Shopping malls comprised of multiple connected establishments.
Service	Buildings in which some type of service is provided, other than food service or retail sales of goods.

1 https://www.eia.gov/consumption/commercial/

Considering the objective of outlining a common framework for the analysis, the selection has been limited to the above-mentioned typologies, as they constitute the principal built-environments that can be evaluated within a common global methodology. In fact, according to their principal activities and occupants, no precise specifications are required to categorize these buildings, neither in terms of indoor environment, operational strategies, nor architectural and structural design.
Among the typologies listed in Table 1, the development of this work started with the office buildings. The choice was driven by two main reasons: first, there is a strong link between IEQ conditions and occupants within this type of building where insufficient conditions can affect both the wellbeing and the health of occupants, as well as other parameters such as productivity. Secondly, offices, because of their intrinsic characteristics, somehow include all the aspects and environmental factors that, in a second phase, can be adjusted and extended to the other building typologies.
Although the replication of the findings to other building typologies other than offices is possible, care should be exercised when considering the specific application context and any related peculiar needs that may help define the boundary conditions for the definition of regenerative indoor environments.

2 CHARACTERIZATION OF A REGENERATIVE ENVIRONMENT

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CONTENT

2.1 THE REGENERATIVE ENVIRONMENT

2.1.1 THE PARADIGMATIC SHIFT (FROM SUSTAINABLE TO RESTORATIVE TO REGENERATIVE): CURRENT REQUIREMENTS FOR THE INDOOR ENVIRONMENT

Rapid industrialization and population growth have contributed to the development of buildings and cities that interact with their surrounding environment and users. Development has generally focused on fulfilling certain aesthetical and functional needs, as well as fixed levels of comfort and cost efficiencies. Minimal consideration has been given to whether our human habitats are well founded within and are in harmony with the natural environment and human life. The extensive damage that human activity has done to our planet and ecosystems is increasingly acknowledged in scientific reports [IPCC 2019]. There is growing recognition we have no planet B and that addressing the issues of global warming, ecological loss, mass extinction, environmental damage and pollution may be the most concerning challenges of our day and age.

However, current sustainability policies and practices are not yet on course to meet these challenges. Sustainable development must replace *'the growth at any price'* philosophy and must drive the choices and the actions of citizens, communities, businesses, scientists and governments. If designers are to be catalysts of positive and regenerative change, they need to create and to retrofit buildings. Design can no longer be merely concerned with developing artefacts that only reduce environmental impacts within a specified target, or that only reduce health-related impacts within certain emission thresholds. Instead, buildings must be developed with the aim of enhancing the relationships between natural systems, the built environment, and inhabitants over long time spans [Naboni and Havinga, 2019].

Restore WG1 (Sustainability Restorative to Regenerative) [Brown et al., 2018] identified our need, as Seva has described, to move from a human-centric eco perspective to a paradigm that sees ourselves and our buildings as a part of nature, rather than apart from nature. We should use the expression of 'human habitats' to recognize that our built environment is part of a wider eco system.

2.1.2 NEW REGENERATIVE OBJECTIVES TO BE PURSUED AND WHY

Among newly constructed buildings, 'green buildings' are now relatively common and regulations and certifications have become more ambitious [Naboni and Edwards, 2012]. Although these are known as 'green' buildings, because their environmental performance is higher in comparison with typical buildings, they are broadly aimed at only reducing 'negative' impacts [Naboni and Havinga, 2019]. Generally, indoor spaces of sustainable buildings are aimed at:

- reducing the potential environmental damage from emissions;
- reducing the contributions to global environmental damage;
- reducing resource use – energy, water, materials;
- minimizing discomfort for building occupants;
- minimizing harmful substances and irritants within building interiors.

However, the targets fixed in the Paris Climate Agreement (PCA) [UNCC, available online], known as the United Nations Sustainable Development Goals (UN SDGs) [UN SDG, available online], and those in the recent Intergovernmental Panel on Climate Change (IPCC) reports, in particular 'Global warming of 1.5°C' [IPCC 2019, available online], will never be achieved by simply slowing down the rates of environmental degradation with such adverse effects on human health. The above lists of 'green' aims are inadequate to meet PCA and UN SDGs.

It is becoming increasingly clear that a net-positive approach is needed to meet these targets, to undo the damage that has already been done, to create ecological gain, and to 'heal the future'. Moreover, whilst the complex challenges surrounding sustainable development have traditionally been viewed through a reductionist mono-disciplinary lens, the proactive UN global Sustainability Development Goals can only be addressed through a collaborative, inter-disciplinary holistic approach. Rephrasing the above-listed attributes of a sustainable building to reflect a net-positive and holistic approach would therefore imply a truly sustainable building with indoor spaces that are designed to:

- reverse environmental damage from emissions;
- contribute to global environmental regeneration;
- create new energy, clean water, and materials through circular approaches;
- promote salutogenic comfort and wellbeing among building occupants;
- select ecological substances that are solely beneficial to humans and the environment within the building.

A NEW LEXICON FOR REGENERATIVE ENVIRONMENTS

from REDUCING – to REVERSING (environmental damage)

from REDUCING – to CONTRIBUTING (to regeneration)

from REDUCING (waste) – to CREATING (circular growth)

From MINIMIZING – to SALUTOGENIC (wellbeing)

From MINIMIZING – to USING SOLELY (healthy materials)

2.1.3 FOCUS ON SALUTOGENESIS

Regenerative design is built on the awareness that humans and the built environment co-exist together within natural systems. As such, Regenerative Design is aimed at reversing the damage that has been done, restoring ecosystems, so that they will thrive and evolve. As regards the design of spaces, regenerative design places occupant wellbeing centre stage. Here, the salutogenic focus is on making wellbeing part of the regenerative paradigm, rather than the reductionist approach of sustainable design that targets the absence of ill health. The term salutogenesis, coined by Aaron Antonovsky, means ‘generation of health’ [Naboni and Havinga, 2019 a]. One key reference within this section is to standards such as the Well Building Standard that aims at implementing, validating, and measuring features that promote human health and wellness.

It must also be noted that the World Health Organisation defines health as *a state of complete physical, mental and social wellbeing* and not just freedom from illness. It helps define the scope within which interior design should focus on human health, whilst providing regenerative co-benefit to planetary health.

‘*Simple concepts like comfort, joy and* aesthetics have had no place in traditional hospitals,’ notes Jan Golembiewski in her article ‘Salutogenic design – The neural basis for health promoting environments’, ‘yet they are the psychological bricks and mortar of all healthy buildings whether or not they are health care buildings.’ [Golembiewski, available online]

In the same way as we now often monitor and display, in real time, the water energy and air-quality performance of a building, the public health sector has perhaps made even more impressive advances, by real-time monitoring of such health issues as asthma and diabetes. It is a logical development to link smart building performance monitoring with smart health monitoring devices. By doing so, we add a new dimension to the building performance gap: the negative or positive impact of a building on the health of its occupants [Brown, 2016].

In FutuREstorative, [Brown, 2016] asked us to imagine the synergy of smart building performance data, combined with real-time health data and embedded within a Building Information Modelling (BIM) system, that can not only be used for future design, but also for real time, net-positive health interventions.

The purpose of this section is to outline several Key Performance Indicators (KPIs) that relate to the design of indoor spaces and that will support a radical shift from merely limiting health-related impacts, to a series of newer regenerative performances. KPIs that will fully embrace the meaning(s) of health generation and wellbeing, facilitating the likely effects and prospects for the development of indoor designs, construction and technologies.

2.2 KEY PERFORMANCE INDICATORS FOR THE EVALUATION OF A REGENERATIVE BUILT ENVIRONMENT

Regenerative Design focuses on salutogenic health and designs that are socially and culturally 'just' and ecologically robust. Designs for indoor and outdoor environments must demonstrably improve inhabitant health, and not merely seek to reduce ill-health. Regenerative Design is therefore an approach that aims to create a new set of relationships that reinforce the state of health of human and natural ecosystems, utilizing appropriate designs, construction methodologies and technology. This challenge implies in-depth knowledge of multiple fields of performance, and state-of-the-art technologies, hence the involvement of several specialists and tools, both to develop approaches and for framing their solutions.

2.2.1 CONVENTIONAL COMFORT AREAS

Four main conventional comfort areas have been considered and assessed in the literature over past decades, in the context of Indoor Environmental Quality (IEQ) conditions within buildings: air quality, hygro-thermal environment, visual environment, acoustic environment. These aspects are strictly connected with the wellbeing of occupants and potential sick-building syndrome, as well as energy and sustainability issues. Moreover, temperature, lighting, sound and vibration, indoor air quality and personal control are among the factors with the greatest effects on working productivity [Fisk and Rosenfeld, 1997] [Fisk, 2002], although over and above these parameters, it would be better to discuss the comfort levels and the perceptions that users associate with them. These four environmental areas have been assessed in several research campaigns [Heinzerling et al., 2013], by means of microclimatic parameters and in situ monitoring campaigns, along with the subjective responses supplied by the building users.
With regard to the Post-Occupancy Evaluation (POE) of buildings (discussed and detailed in Chapter 5), parameters and performance indicators are identified to set requirements taken from scientific research for the evaluation of indoor quality conditions. The POE procedures and example case studies are framed within national and international standards.
In addition to providing information on the different Key Performance Indicators (KPIs) and assessment methods, regulatory values and thresholds for each parameter are reported (both for objective and subjective monitoring). Some of the environmental parameters are often found in more than one standard and different requirements for the same indicator are not unusual. An uncertainty over standardization that complicates the navigation of regulations, the interpretation of specifications, and an understanding of the required performance levels.
The aim of this part of the work is to simplify such readings and to outline a common framework for identifying a set of KPIs and assessing appropriate thresholds, which will prove suitable for the characterization of regenerative commercial buildings.

Regenerative Indoors within Commercial Buildings

The intrinsic characteristics of an office include all the aspects and environmental factors which, in a second phase, can be extended and adapted to other building typologies. The Indoor Environmental Quality (*IEQ)* conditions of offices affect occupant productivity to a high degree and, given that the workplace is where almost 90% of our time within a building is spent, insalubrious conditions within these spaces can negatively impact on worker wellbeing and health. In fact, different discomfort issues can severely decrease task-performance capabilities, which will in the end have adverse long-term health effects [Naboni and Edwards, 2012].
Productivity, in terms of attention levels, cognitive effort, decision-making capabilities, information processing, and writing capabilities, are strictly related to indoor air quality and thermal comfort, which can also provoke symptoms of ill-health [Wargocki and Wyon, 2017]. The visual environment is particularly important for reading purposes, both desk and screen, and a good space layout can promote visual privacy and enhance the working experience [De Carli et al., 2008] [Webb, 2006]. Acoustic features directly impact on auditive effort, sound privacy, communication and, in the end, task performance [Errett et al., 2006] [Lee and F. Aletta, 2019]. Both visual and acoustic aspects can also be harmful for human health [Boyce, 2010] [Park et al., 2018], in terms of visual problems and acoustic pathologies, and lacking comfort aspects can, in the end, negatively affect psychological mood and working attitudes.

2.2.2 FRAMEWORK FOR ANALYSING THE MAIN INDOOR ENVIRONMENTAL ASPECTS OF A BUILDING

A three-step methodological framework was developed and applied to the office buildings, in order to investigate the selected building in a structured and repeatable manner. The three steps detailed below are: (i) Building information; (ii) Building environment; (iii) Literature review.

2.2.2.1 BUILDING INFORMATION (TABLE 1)

a) Typology: offices
b) Function: buildings used for general office space, professional and/or administrative offices.
c) Target occupants: *adults*

2.2.2.2 BUILDING ENVIRONMENT

a) Main related tasks and parameters potentially affected: productivity, attention, cognitive activities, processing information, writing capability, visual privacy, desk reading, screen reading, auditory ease, sound privacy, health-related absenteeism, psychological attitudes and motivation;
b) Environmental aspect: air quality, hygro-thermal environment, visual environment, acoustic environment;
c) Environmental sub-aspects:
    i air quality: outdoor/indoor ventilation, chemical/natural contaminants, concentrations, odours, occupant satisfaction levels;
    ii. hygro-thermal environment: temperature, humidity, local discomfort, occupant satisfaction levels;
    iii. visual environment: natural/artificial lighting, glare, colour rendering, circadian rhythm, occupant satisfaction levels;
    iv. acoustic environment: background noise level, sound absorption/reflection reverberation, acoustic insulation, occupant satisfaction levels.

2.2.2.3 LITERATURE REVIEW

At this stage, following a search of the current available international standards, the conventional parameters have been listed and organized in accordance with their required values. The main findings are reported below, in Tables 2 to 6.

Table 2. Framework for the building typology analysis: building information and environmental aspects.

Building information			**Building environment**		
Typology	**Function**	**Target occupants**	**Affected tasks**	**Aspects**	**Sub-aspects**
Offices	Buildings used for general office space, professional and/or administrative offices. [1]	Adults	• Productivity • Attention • Cognitive activities • Processing information • Writing capability • Visual privacy • Desk reading • Screen reading • Auditory ease • Sound privacy • Health-related absenteeism • Psychological attitudes and motivation	**Air quality**	outdoor/indoor ventilation chemical/natural contaminants concentrations odours occupant satisfaction
				Hygro-thermal	temperature humidity local discomfort occupant satisfaction
				Visual	natural/artificial lighting glare colour rendering circadian rhythm occupant satisfaction
				Acoustic	background noise level sound absorption/reflection reverberation acoustic insulation occupant satisfaction
				Human nature	external view right to light biophilia access to nature

Table 3. Framework for the building typology analysis: air quality in currently available standards and conventional parameters

State of the art: AIR QUALITY		
Available literature sources and standards	**Current conventional parameters and values**	
EPA, ***National Ambient Air Quality Standards*** **(outdoor requirements)** [U.S. Environmental Protection Agency (EPA), available online (a)]	Carbon monoxide	9 ppm / 35 ppm [1h]
	Lead	1.5 µg m-3 [3months]
	Nitrogen dioxide	0.05 ppm [1yr]
	Ozone	0.12 ppm [1h] / 0.08 ppm
	Particles <2.5 µm MMAD	15 µg m-3 [1yr] 15 µg m-3 [1yr] 35 µg m-3 [24h]
	Particles <10 µm MMAD	150 µg m-3 [24h]
	Total particles	0.03 ppm [1yr] / 0.14 ppm [24h]
WHO, ***Air Quality Guidelines for Europe*** **(outdoor and indoor requirements)** [World Health Organization (WHO), 2000]	Carbon monoxide	90 / 50 / 25 / 10 ppm [15/30min 1/8h]
	Formaldehyde	0.1 mg m-3 (0.081 ppm) [30min]
	Lead	0.5 µg m-3 [1yr]
	Nitrogen dioxide	0.1 ppm [1h] / 0.02 ppm [1yr]
	Ozone	0.064 ppm (120 µg m-3) [8h]
	Sulphur dioxide	0.048 ppm [24h] / 0.012 ppm [1yr]
NIOSH, ***Pocket Guide to Chemical Hazards*** **(outdoor requirements)** [U.S. National Institute for Occupational Safety and Health (NIOSH), available online]	Carbon dioxide	5,000 ppm / 30,000 ppm [15min]
	Carbon monoxide	35 ppm / 200 ppm [ceiling]
	Formaldehyde	0.016 ppm / 0.1 ppm [15min]
	Lead	0.050 mg m-3
	Nitrogen dioxide	1 ppm [15min]
	Ozone	0.1 ppm [ceiling]
	Sulphur dioxide	0.050 mg m-3
OSHA, ***Code of Federal Regulations*** **(outdoor requirements)** [U.S. Occupational Safety and Health Administration (OSHA), available online]	Carbon dioxide	5,000 ppm
	Carbon monoxide	50 ppm
	Formaldehyde	0.75 ppm / 2 ppm [15min]
	Lead	0.05 mg m-3
	Nitrogen dioxide	5 ppm [ceiling]
	Ozone	0.1 ppm
	Sulphur dioxide	5 ppm
	Total particles	15 mg m-3

State of the art: AIR QUALITY		
Available literature sources and standards	**Current conventional parameters and values**	
ANSI/ASHRAE, ***Standard 62.1*** **(indoor requirements)** [American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2016]	Carbon monoxide	9 ppm [8h]
	Formaldehyde	0.1 mg m-3 / 0.081 ppm [30min] 27 ppb [8h] 45 ppb / 7.3 ppb [1h/8h] 16 ppb based on different levels of health effects
	Lead	1.5 µg m-3
	Nitrogen dioxide	100 µg m-3 470 µg m-3 [24h averaged]
	Odours	80 % acceptability among occupants
	Ozone	100 µg m-3 / 50 ppb
	Radon	4 pCi/L
	Sulphur dioxide	80 µg m-3
	VOCs	Determined for each individual compound [Refer to: ANSI/ASHRAE, Standard 62.1, Table C-3]
	Particles <2.5 µm MMAD	15 µg m-3
	Particles <10 µm MMAD	50 µg m-3
	Ventilation rate	5 L s-1· person-1
ANSI/ASHRAE, ***Fundamentals 2017*** **(outdoor and indoor requirements)** [American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2017]	Contaminants	Values adapted from EPA (outdoor). Values adapted from ASHRAE Standard 62.1 (indoor).
CEN, ***UNI EN 16798-1*** **(indoor requirements)** Comité Européen de Normalisation (CEN) [European Committee for Standardization, 2019]	Carbon-dioxide	For non-adapted persons: 550 ppm above outdoor for Cat. I 800 ppm above outdoor for Cat. II 1350 ppm above outdoor for Cat. III 1350 ppm above outdoor for Cat. IV
	TVOCs	< 1000 µg m-3 / < 300 µg m-3 *
	Formaldehyde	< 100 µg m-3 / < 30 µg m-3 *
	* Depending on low/very low polluting buildings	
	Design ventilation air flow for single-person office of 10 m2 in a low polluted building (non-adapted person)	1.0 l s-1 m-2 for Cat. I 0.7 l s-1 m-2 for Cat. II 0.4 l s-1 m-2 for Cat. III 0.3 l s-1 m-2 for Cat. IV OR 10 l/(s per person) for Cat. I 7 l/(s per person) for Cat. II 4 l/(s per person) for Cat. III 2.5 l/(s per person) for Cat. IV

State of the art: AIR QUALITY		
Available literature sources and standards	**Current conventional parameters and values**	
IWBI, ***The WELL Building Standard*** [International Well Building Institute (IWBI), 2019]	Formaldehyde	< 27 ppb
	TVOCs	< 500 μg m-3
	Carbon monoxide	< 9 ppm
	$PM_{2.5}$	< 15 μg m-3
	PM_{10}	< 50 μg m-3
	Ozone	< 51 ppb
	Radon	< 0.148 Bq/L
	For ventilation design, refer to: EPA, National Ambient Air Quality Standards ANSI/ASHRAE, Standard 62.1 Other US local regulations	
The Living Building Challenge V 3.1 *Health and Happiness Handbook,* International [Living Future Institute (ILFI), 2016]	Indoor Healthy Environment	A project must create a Healthy Indoor Environment Plan, to promote good indoor air quality, which will explain the steps for the project to achieve an exemplary indoor environment, by including the following: Compliance with the current version of ASHRAE 62, or international equivalent; Results from Indoor Air-Quality (IAQ) tests before and nine months after initial occupancy; Compliance with the California Department of Public Health (CDPH) Standard Method v1.1-2010 (or international equivalent) for all interior building products that have the potential to emit Volatile Organic Compounds; Dedicated ventilation systems for kitchens, bathrooms and janitorial areas; An entrance routine that detaches particulate matter on shoes; An outline of a cleaning protocol that uses cleaning products that comply with the EPA Design for Environment label (or international equivalent).
	Formaldehyde	< 50 ppb
	$PM_{2.5}$	< 12 μg m-3
	PM_{10}	< 150 μg m-3
	TVOCs	< 500 μg m-3
	4-Phenylcyclohexane	< 3 μg m-3
	Carbon monoxide	< 9 ppm
	Ozone	< 51 ppb
	Carbon dioxide	< 750 ppm
	Nitrogen dioxide	< 0.053 ppm [24h period]

Table 4. Framework for the building typology analysis: hygro-thermal environment current available standards and conventional parameters

<table>
<tr><th colspan="7">State of the art: HYGRO-THERMAL ENVIRONMENT</th></tr>
<tr><th>Available literature sources and standards</th><th colspan="6">Current conventional parameters and values</th></tr>
<tr><td rowspan="9">ANSHI/ASHRAE,
Standard 55
[American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2013]</td><td>Comfort zone method-operative temperature, applicable with
1.0 ≤ met ≤ 1.3
0.5 ≤ clo ≤ 1.0
V_a ≤ 0.2 m s^{-1}
Humidity ratio ≤ 0.012 kg · H_2O/kg
Occupant-controlled operable windows</td><td colspan="5">See ranges in: ANSHI/ASHRAE, Standard 55, Figure 5.3.1</td></tr>
<tr><td>Temperature Drifts and Ramps</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Time period (h)</td><td>0.25</td><td>0.5</td><td>1</td><td>2</td><td>4</td></tr>
<tr><td>Maximum Operative Temperature Change Allowed, °C</td><td>1.1</td><td>1.7</td><td>2.2</td><td>2.8</td><td>3.3</td></tr>
<tr><td>SET method, applicable with
V_a ≥ 0.2 m s^{-1}
(for evaluating cooling effect)
Mechanically conditioned buildings</td><td colspan="5">Calculation of Adjusted PMV (PMV_{adj})</td></tr>
<tr><td>PMV/PPD method, applicable with
1.0 ≤ met ≤ 2.0
clo ≤ 1.5
V_a ≤ 0.2 m s^{-1}
Mechanically conditioned buildings</td><td colspan="5">-0.5 < PMV < +0.5
(= 90 % users satisfied)
PPD < 10 %</td></tr>
<tr><td>Local thermal discomfort, applicable with
1.0 ≤ met ≤ 1.3
0.5 ≤ clo ≤ 0.7</td><td colspan="5">Expected PPD [%]:
- Draft: < 20 %
- Vertical Air Temperature Difference: <5 %
- Warm or Cool Floors: < 10 %
- Radiant Asymmetry: < 5 %</td></tr>
<tr><td>Occupant satisfaction levels</td><td colspan="5">Thermal acceptability with ≥ 80 %</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td rowspan="6">**CEN, *UNI EN 16798-1***
[CEN, 2019]</td><td colspan="6">PMV/PPD method, applicable with mechanical heating/cooling</td></tr>
<tr><td>Category</td><td colspan="2">PMV</td><td colspan="3">PPD [%]</td></tr>
<tr><td>I
II
III
IV</td><td colspan="2">-0.2 < PMV < +0.2
-0.5 < PMV < +0.5
-0.7 < PMV < +0.7
PMV < -0.7; or +0.7 < PMV</td><td colspan="3">< 6
< 10
< 15
> 15</td></tr>
<tr><td colspan="6">Design criteria: Operative temperature [°C]</td></tr>
<tr><td>Category*</td><td colspan="2">Minimum for heating (winter s.), ~1.0 clo sedentary ~1.2 met</td><td colspan="3">Minimum for cooling (summer s.), ~0.5 clo sedentary ~1.2 met</td></tr>
<tr><td>I
II
III
IV</td><td colspan="2">21.0
20.0
19.0
18.0</td><td colspan="3">25.5
26.0
27.0
28.0</td></tr>
</table>

State of the art: HYGRO-THERMAL ENVIRONMENT

Available literature sources and standards	**Current conventional parameters and values**
	* Both for single and open-plan offices ** Assuming 50% RH and <0.1 m s^{-1} air velocity
	Running mean outdoor temperature, applicable in summertime, with no cooling system — For ranges of indoor temperatures, see: CEN, UNI EN 16798-1, ANNEX H.2

Design criteria: Relative humidity [%]

Category*	For dehumidification	For humidification
I	50	30
II	**60**	**25**
III	70	20

* In occupied spaces with systems installed

CEN, *EN ISO 7730*
[CEN, 2005]

	Design criteria: Operative temperature [°C]		Design criteria: Max mean air velocity [m s^{-1}]	
Category*	Summer	Winter	Summer	Winter
A	24.5 ± 1.0	22.0 ± 1.0	0.12	0.10
B	24.5 ± 1.5	22.0 ± 2.0	0.19	0.16
C	24.5 ± 2.5	22.0 ± 3.0	0.24	0.21 **

* With activity 70 W m^{-2} — ** Below 20 °C limit

PMV/PPD method

Category	PMV	PPD [%]
I	-0.2 < PMV < +0.2	< 6
II	**-0.5 < PMV < +0.5**	**< 10**
III	-0.7 < PMV < +0.7	< 15
IV	PMV < -0.7; or +0.7 < PMV	> 15

Local discomfort: PD [%]

Category	Vertical air t difference	Warm/cool floor	Radian asymmetry
A	<3	<10	<5
B	<5	<10	<5
C	<10	<15	<10

Local thermal discomfort
*1.1 and 0.1 m above floor

Category	Floor surface temperature range [°C]	Draught Rate [%]
A	19 to 29	10
B	19 to 29	20
C	17 to 31	30

Local thermal discomfort: Radiant temperature asymmetry [°C]

State of the art: HYGRO-THERMAL ENVIRONMENT					
Available literature sources and standards	**Current conventional parameters and values**				
	Category	Warm ceiling	Cool wall	Cool ceiling	Warm wall
	A B C	<5 <5 <7	<10 <10 <13	<14 <14 <18	<23 <23 <35
ANSHI/ASHRAE, *Fundamentals 2017* [American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2017]	In accordance with ANSHI/ASHRAE, Standard 55				
IWBI, *The WELL Building Standard* [International Well Building Institute (IWBI), 2019]	Refers to ANSI/ASHRAE, Standard 55				

Table 5. Framework for the building typology analysis: visual environment current available standards and conventional parameters

State of the art: VISUAL ENVIRONMENT				
Available literature sources and standards	**Current conventional parameters and values**			
CEN, *EN 12464-1* [CEN, 2004]	Activity	E_m [lux]	UGRL	R_a
	Filing Writing, reading, data processing Graphic CAD desks Conference rooms * Reception Archives	300 500 750 500 500 300 200	19 19 16 19 19 22 25	80 80 80 80 80 80 80
	* Lighting must be adjustable			
CEN, *UNI EN 16798-1* [CEN, 2019]	E_m [lux] for Offices - Writing, typing, reading, data processing, conference and meeting rooms	500		
CIBSE, *Daylighting and Window Design Guide* [CIBSE Lighting Guide]	<u>Daylight factor</u> The higher the Daylight Factor (DF), the more daylight is available in the room. Rooms with an average DF of 2% or more can be considered daylit, but electric lighting may still be needed to perform visual tasks. A room will appear strongly daylit when the average DF is 5% or more, in which case electric lighting will most likely not be used during the daytime.			
BRE, *BREEAM* [BREEAM]	<u>Daylight factor</u> At least 80% of floor area in occupied spaces has an average daylight factor of 2% or greater.			
USGBC, *LEED* [USGBC]	<u>Daylight illuminance levels</u> Computer simulation shows the applicable spaces as having daylight illuminance levels of a minimum of 25 foot-candles (fc) (270 lux) and a maximum of 500 fc (5400 lux) under clear sky conditions, on September 21, at 9 a.m. and 3 p.m. Areas with illuminance levels below or above the range do not comply. However, designs that incorporate view-preserving automated shades for glare control may demonstrate compliance for only the minimum 25 fc (270 lux) illuminance level.			

State of the art: VISUAL ENVIRONMENT	
Available literature sources and standards	**Current conventional parameters and values**
DGNB [German Sustainable Building Council]	Daylight factor 50% of the usable area throughout a building has a DF (>3% very good, >2% medium, >1% slight, <1% none). Based on simulations, the daylight is classified in permanently used work areas (3% ≤ DF very good, 2.5% ≤ DF < 3% medium, 2% ≤ DF <2.5% slight, DF <2% none).
IES [Illuminating Engineering Society]	Daylight autonomy The Illuminating Engineering Society based in North America currently promotes the following values: a target illuminance of 300 lux and a threshold Daylight Autonomy of 50%, meaning 50% of the time daylight levels are above the target illuminance.
Daylighting, Artificial Lighting and Non-Visual Effects Study for a Residential Building [Nabil and Mardaljevic, 2012]	Useful Daylight Illuminance (UDI) Daylight illuminances in the range 100 to 300 lux are considered effective, either as the sole source of illumination or in conjunction with artificial lighting. Daylight illuminance values within the range of 300 to ±3 000 lux are often perceived as desirable.
IWBI, *The WELL Building Standard* [International Well Building Institute (IWBI), 2019]	Circadian rhythms: Equivalent Melanopic Lux (EML) Light models or light calculations demonstrate that at least one of the following requirements is met: a. At 75% or more of work-stations, an equivalent of at least 200 melanopic lux will be present, measured on the vertical plane facing forward, 1.2 m [4 ft], above floor level (to simulate the view of the occupant). This light level may incorporate daylight and it is at least present during the hours between 9:00 AM and 1:00 PM every day of the year. b. For all workstations, electric lights provide maintained illuminance on the vertical plane facing forward (to simulate the view of the occupant) of 150 equivalent melanopic lux or greater.
The Living Building Challenge V 3.1 *Health and Happiness Handbook,* [International Living Future Institute (ILFI), 2016]	Civilized Environment To provide access to both fresh air and daylighting, all regularly occupied spaces must meet the following specific criteria: • Provide daylighting appropriate for use through at least one window wall (at least 10% glazed) per space (There is no set maximum glass area, since the project will be limited by the demands of the Net Zero Energy Petal. Project teams are encouraged to take into account the acceptable range for daylight factors based on the function of the space). Allow occupant control of fresh air and tangible access to the outdoors. Locate staffed workstations: - Within 9 m (30 ft.) of operable windows; - Proximal to partitions no higher than 110 cm (3’7”) when in the line of sight of windows.

Table 6. Framework for the building typology analysis: acoustic environment current available standards and conventional parameters

<table>
<tr><th colspan="5">State of the art: ACOUSTIC ENVIRONMENT</th></tr>
<tr><th>Available literature sources and standards</th><th colspan="4">Current conventional parameters and values</th></tr>
<tr><td rowspan="5">CEN, UNI EN 16798-1
[CEN, 2019]</td><td colspan="4">Equivalent continuous sound level Leq, nT,A [dB(A)]</td></tr>
<tr><td>Type of office</td><td>I</td><td>II</td><td>III</td></tr>
<tr><td>Small offices</td><td>≤ 30</td><td>≤ 35</td><td>≤ 40</td></tr>
<tr><td>Landscaped offices</td><td>≤ 35</td><td>≤ 40</td><td>≤ 45</td></tr>
<tr><td>Conference rooms</td><td>≤ 30</td><td>≤ 35</td><td>≤ 40</td></tr>
<tr><td rowspan="10">IWBI, The WELL Building Standard
[International Well Building Institute (IWBI), 2019]</td><td colspan="2">Average sound pressure level from outside noise intrusion</td><td colspan="2">≤ 50 dBA *

*as measured when the space and adjacent spaces are unoccupied, but within 1 hour of normal business hours</td></tr>
<tr><td colspan="4">Noise criteria (NC)</td></tr>
<tr><td colspan="2">Open office spaces and lobbies that are regularly occupied and/or contain workstations</td><td colspan="2">max 40</td></tr>
<tr><td colspan="2">Enclosed offices</td><td colspan="2">max 35</td></tr>
<tr><td colspan="2">Conference rooms and breakout rooms</td><td colspan="2">max 30 (25 recommended)</td></tr>
<tr><td colspan="4">Reverberation time (RT60)</td></tr>
<tr><td colspan="2">Conference rooms</td><td colspan="2">0.6 sec</td></tr>
<tr><td colspan="2">Open workspaces</td><td colspan="2">0.5 sec</td></tr>
<tr><td colspan="4"><u>If sound-masking systems are used, sound levels</u> fall within the following ranges, when measured from the nearest workspace:

Open workspaces 45-48 dB

Enclosed offices 40-42 dB</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Other national standards and regulations</td><td colspan="4">According to the legislation of each Member State</td></tr>
</table>

2.3 KPI THRESHOLDS AND SUGGESTED VALUES: TOWARDS A TECHNOLOGY FOR A REGENERATIVE BUILT ENVIRONMENT

Starting with the information collected from the available sources, explained in the previous paragraph, a list of Key Performance Indicators was developed.

In addition to the environmental aspects shown in Tables 2 to 6, from the perspective of a regenerative indoor environment that will boost occupant satisfaction levels, health and wellbeing, some human-related values were included in the first analysis, as in Table 7. These values are mainly related to the view of the outdoors and to biophilia. It opens up new possibilities, not only to explore integrated regenerative performance, but also to create inspiring environments, which can be described in a new set of geometrical relationships.

Table 7. Framework for the building typology analysis: human values in current available standards and parameters

State of the art: HUMAN NATURE ENVIRONMENT	
Available literature sources and standards	Current conventional parameters and values
IWBI, *The WELL Building Standard* [International Well Building Institute (IWBI), 2019]	External view and right to light - 75% of all workstations are within 7.5 m [25 ft] of an atrium or a window with views to the exterior. - 95% of all workstations are within 12.5 m [41 ft] of an atrium or a window with views to the exterior. Biophilia and access to nature - Potted plants or planted beds cover at least 1% of the floor area per floor. - A plant wall per floor, covering a wall area equal to or greater than 2% of the floor area, or covering the largest of the available walls, whichever is greater.
ILFI, *Living Building Challenge* [International Living Future Institute (ILFI), 2016]	External view and right to light Provide views to the outside and daylight for 75% of occupants. The project must be designed to include elements that will nurture the innate connection between humans and nature. Each project team must engage in an exploration of the biophilic design potential of the project over a minimum of one full-day. The exploration must result in a biophilic framework and a project plan that outlines the following: • How the project will be transformed by deliberately incorporating nature through Environmental Features, Light and Space, and Natural Shapes and Forms • How the project will be transformed by deliberately incorporating patterns from nature through Natural Patterns and Processes and Evolved Human-Nature Relationships. • How the project will be uniquely connected to the place, climate and culture through Place-Based Relationships. • The provision of sufficiently frequent human-nature interactions in both the interior and exterior of the project building, so that the majority of occupants enter into direct contact with nature.

With these pieces of information, a list of KPIs is proposed, focusing on the achievement of a regenerative indoor environment. The objective of these KPIs is, in fact, to overcome the simplistic and limited concept of a sustainable building, in which the indoor environment is acceptable and fulfils the standard specifications. The aim is to achieve indoor conditions that will improve user experiences, health, wellbeing, psychological mood and attitudes, and life in general.

Thus, the approach towards preparing this list of KPIs consisted neither of nullifying nor of erasing the regulatory requirements. Instead, it was intended as a step towards the achievement of a better indoor environment and reconnection with natural elements. With these premises, the indicators identified in the state of the art underwent a filtering process, aiming at a number of KPIs ≈ 10, to be delivered as an additional and useful tool for helping the designer to develop regenerative buildings. For each KPI, a regenerative threshold is proposed, as shown in Table 8. As may be observed, besides the objective parameters that may be monitored with specific instrumentation, subjective ones are also introduced, i.e. the percentage of satisfied people assessed by means of *POE survey questionnaires.*

Table 8. Final list of KPIs and proposed values

Environmental aspect	Sub-aspect	KPI	Regenerative values
Air Quality Environment	*Contaminants*	Formaldehyde	≤ 0.1 mg m^{-3} [30 min]
	Outdoor/Indoor	Particulate matter: PM_{10} $PM_{2.5}$	< 150 µg m^{-3} [24h] < 12 µg m^{-3} [1yr]
	Occupant satisfaction	% satisfied people	80 %*
Hygro-Thermal Environment	*Temperature/ humidity/air speed*	Implementation of ASHRAE 55	ASHRAE 55 + evaluation of air movement
	Occupant satisfaction	% satisfied people	80 % *
Visual Environment	*Daylight*	Useful Daylight Illuminance	300 – 3000 lux
	Circadian Rhythms	Equivalent Melanopic Lux	≥ 200 (9am-1pm) **
	Occupant satisfaction	% satisfied people	80 % *
Acoustic Environment	*Background noise level*	Noise criteria	≤ 30 / ≤ 40 ***
	Occupant satisfaction	% satisfied people	80 % *
Human Nature Environment	*Right to light*	% with windows access to daylight	100 % of inhabitants
	Connectivity to Nature (Biophilia)	Intentional interior design interventions that bridge the gap between natural and built environments.	4. Biophilic Design Workshop held prior to design. 5. Biophilic Interventions incorporated: 7/14 Biophilic Patterns [Browning et al. 2014]. 6. POE *Connectivity with Nature* satisfaction.

* response rate representing at least one quarter of the total number of building/indoor environment users. Although a value of 100% is desirable, and in some cases like hygro-thermal comfort is achievable with the use of personal comfort systems [Pasut et al., 2015], we are aware that there will always be a percentage of people that despite all efforts may never be satisfied. For this reason, we aim at a value that is 80% or higher.

** for 75 % or more workstations.

*** enclosed / open offices.

ANNEX 1 lists the definitions of the KPIs.

The choice of the final KPIs and their thresholds were aimed at overcoming the common idea of a sustainable building, in the new perspective of a regenerative indoor environment. A performance indicator was chosen and its thresholds were identified for each aspect (e.g., air quality, hygro-thermal, visual, acoustic, human values) selected from among those identified in the literature.

Air quality plays a pivotal role in the indoor environment, since it is well known to affect the health of occupants, and their wellbeing and working performance [Tham, 2016]. It is even more important in office buildings, where insufficient air-quality standards can cause health-related absenteeism, with consistent implications for individual performance, and therefore for overall productivity and economic activity [Fisk et al., 2011].

As can be observed in Table 3, the topic of air quality is a highly controversial one, since the actual effects on human health have yet to be clearly quantified. Each standard therefore lists its own specifications, based on different research studies, which in consequence leaves a great variety of parameters and ranges, navigating which is often difficult. Among the various indicators that have been identified in the literature, formaldehyde and particulate matter have been selected as additional values for assessment within indoor environments.

Formaldehyde is a colourless gas often present within indoor environments, to which users can simply be exposed through inhalation [U.S. Environmental Protection Agency (EPA)], available online (b)]. Predominant symptoms range from irritation of eyes, nose and throat, lachrymation, sneezing, coughing, nausea, dyspnoea, to cancer and even death following prolonged exposures [World Health Organization (WHO), 2000]. Atmospheric formaldehyde is off-gassed from products and, in buildings, it is mainly found in resins used for the manufacture of composite wood products, building materials and insulation, and household products. Despite its common presence in the indoor environments, and its potentially serious effects on health, there are substantial variations between individual responses to formaldehyde among humans [World Health Organization (WHO), 2000]. For these reasons, ranges of this substance in indoor environments vary greatly between different guidelines and are often weighted according to different exposure times. In fact, exposure should not only be evaluated in terms of concentration, but also in terms of exposure over time. According to WHO, 0.1 mg m-3 is the lowest concentration associated with nose and throat irritation in humans after short-term exposure, although it has been noticed that some individuals can sense the presence of formaldehyde at lower concentrations. Accordingly, an air-quality guideline value of 0.1 mg m-3 as a 30-minute average is recommended, in order to avoid any significant sensory irritation in the general population.

Great attention must be given to construction materials, furniture and products used within the indoor environment, in order to achieve the target value. All the chosen building materials and furniture must have little or no added formaldehyde, and caution must be exercised when using products and combustion appliances that can release formaldehyde. Concentrations of hazardous substances are therefore not solved with increased ventilation rates, but are better prevented, in the first place, by aware usage of building materials and products.

Particulate matter is a key link between indoor and outdoor air. PM_{10} particles are smaller than 10 micrometres in diameter, and high airborne particulate levels can irritate both the eyes and the throat, and can even provoke asthma and other respiratory issues among people with pre-existent conditions. Moreover, $PM_{2.5}$ particles are smaller than 2.5 micrometres in diameter, for which reason they can be inhaled deeply into the lungs, and can cause adverse health effects especially among children, people over 65, pregnant women and people with existing heart or lung conditions [U.S. Environmental Protection Agency (EPA), available online ©]. Indoor PM consists of both airborne particles of outdoor origin that migrate indoors and airborne particles from indoor sources. The latter can be generated through cooking, combustion activities and other hobbies, but they can also be of biological origin [U.S. Environmental Protection Agency (EPA)], available online (d)]. Less is known about indoor particulate matter, but its effects appear to irritate the eyes, the nose and the throat, and can aggravate coronary and respiratory disease symptoms, and premature death among people with heart and lung disease.

According to [World Health Organization (WHO), 2000], data on exposure levels to airborne inhalable particles are still limited for Europe, but studies suggest that short-term variations of exposure to airborne particulate matter are associated with adverse health effects even at low levels of exposure, below 100 µg m-3. However, a threshold below which no effects occur cannot yet be extrapolated on the basis of current data. Most of the currently available studies on airborne particles provide information on PM_{10}, although according to recent consistent information on fine particulate matter and studies, $PM_{2.5}$ generally appears to be a better predictor of health effects than PM_{10} [World Health Organization (WHO), 2000]. As stated above, a large portion of indoor airborne PM is connected with outside air levels, thus, in homes without smoking or other strong particle sources, indoor PM would be expected to be at either the same level or lower than outdoor levels [U.S. Environmental Protection Agency (EPA), available online (d)]. The EPA National Ambient Air Quality Standards [U.S. Environmental Protection Agency (EPA), available

online (a)] specify two types of national ambient air quality standards that are defined in the Clean Air Act and the Amendments of 1990. "Primary standards provide public health protection, including protecting the health of "sensitive" populations such as asthmatics, children, and the elderly. Secondary standards provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings." According to primary requirements, thresholds are set as: less than 150 µg m-3 for PM_{10} averaged over 24 hours and not to be exceeded more than once per year on average over 3 years; less than 12 µg m-3 for $PM_{2.5}$ as an annual mean, averaged over 3 years.
As regards the prevention of PM in the indoor environment, indoor PM levels are clearly connected with outdoor air ranges, but they are also dependent on several other factors, i.e. infiltration, types of ventilation and filtration systems, indoor sources, and occupant activities. Attention must therefore be given to both the choice of efficient HVAC systems and the regulation of their filters, as well as filtration into the building, and the prevention of PM from internal sources, especially from cooking and combustion activities, in order to avoid high levels of PM.
The hygro-thermal aspects of the indoor environment also have a strong impact on occupant wellbeing and, in offices, on task performance capabilities [Naboni, Lee and Fabbri, 2017]. In the studies considered in [Frontczak and Wargocki, 2011], thermal comfort was considered by the building users to be the most important parameter influencing their overall satisfaction levels with IEQ. It was nevertheless strongly influenced by building typology, outdoor climate, seasonal changes, ventilation types, and occupant characteristics, both personal and psychological. Thermal comfort has a strong effect on working performance: according to [Wargocki and Wyon, 2017], as with indoor air quality, six different dynamics can influence task performance at work: (i) attention is negatively affected by thermal discomfort; (ii) manual dexterity is influenced by cold conditions, lowering the temperature of the fingers; (iii) individual attentiveness decreases with warm temperatures, while the likelihood of Sick Building Syndrome (SBS) symptoms is increased, with additional distraction and negative effects on cognition; (iv) slightly raised room temperatures and rapid temperature swings have the same effect on work; (v) poor air quality perceived when inhaling is often caused by vertical thermal gradients, although any reduction in room temperature to solve that issue, may then cause thermal discomfort at floor level due to vasoconstriction; and, finally, (vi) higher CO2 concentrations in the blood, due to raised indoor temperatures, may cause headaches.
The specifications for the assessment of hygro-thermal conditions in indoor environments, detailed in ANSI/ASHRAE 55 [American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2013], are the main reference point, in relation to both the PMV and the adaptive model methods (Table 4). Its requirements must be followed, especially the specifications on air velocity. Air movement can, in fact, be an effective tool both for improving air quality and for thermal sensation [Fountain and Arens, 1993], [Zhai. et al. 2013], [Pasut. et al. 2014].

Visual Environment and Human Nature Values

Daylight plays a key role in providing a good visual, biologically effective and energy-efficient lighting of indoor spaces. When thinking of regenerative daylighting, a shift is necessary, from the idea of providing sufficient light to perform tasks, to the idea of providing the quantity and the quality of light that is coherent with good health. To that extent, the proposed KPIs are daylighting, circadian rhythm and human nature values such as external Views and biophilia [Naboni 2019 b, c].
In indoor spaces, a significant amount of daylight indicates an idea of the time of day and weather and thus represents a relationship to the outside through the respective intensity, distribution and spectral composition. Daylight has a direct biological effect on humans through the control of the circadian rhythm through melatonin suppression mechanisms.
Furthermore, daylighting and human value, such as views, are often related. Providing a line of sight from the inside to the outside is an extremely important psychological factor. In addition, numerous studies have documented the high psychological significance of a visual connection to the outside. Further differentiation is that a view of nature is perceived as more recreational and creativity-promoting than a view of a built-up area, for which reason, the concept of biophilia is included among the KPIs.

Human Nature Values have been included within the scope of Regenerative KPIs, in recognition of the important non-technical and often difficult to monitor aspects that affect our human senses. To thrive as human beings, we require all senses to be satisfied and, importantly, the liminal interconnectivity between senses. The current focus on integrating such aspects into interior environments is through biophilic design. Not only does good connectivity with nature foster good human physical and mental human health, it also fosters improved social connectivity, sustainability behaviours, and productivity.

Human Nature Values should not be considered as an add-on or as "nice to have", but should be seen as a foundation on which to design the technical (light, visual, acoustic, comfort) aspects, hence the inclusion of a Biophilic Design Workshop as a KPI. Moreover, projects should be able to track the effectiveness of biophilic interventions, in keeping with the nature of the project and its location. Finally, the inclusion of 'Connectivity with Nature' satisfaction aspects are also highly encouraged within POE evaluations

In addition, indoor environments should include aspects designed to delight the human spirit through enhanced connectivity with nature.

Acoustics within office buildings can be either a great facilitator for work performance or a great source of distraction and impairment. According to a study commissioned by the U.S. General Service Administration (GSA) in an office building in Philadelphia [General Service Administration (GSA), 2011], 60% of office workers said that if it were quieter, they could get more done, 56% said the ability to insulate themselves from distractions was very important, and 50% said noise stopped them from being as productive as they could be. Despite the problem with distractions and voice privacy, collaboration is often improved in open workspaces. Thus, the current challenge is to maintain the benefits of interaction identifying ways of reducing distractions and enabling speech comprehension.

Among the various issues in the acoustic environment, background noise is among the most basic central issues to be considered, in order to promote good intelligibility in space. Background noise, evaluated with Noise Criteria (NC), is often from equipment and mechanical systems. Legislation and standards on acoustics are both controversial and difficult to navigate, as they will often differ between various national decrees and standards, preventing any homogeneous evaluation of such parameters. According to GSA, private offices should have a "confidential" speech privacy level (≤ 30) and open-plan offices should have a "normal" speech privacy level (≤ 40) (Table 6).

Psychoacoustics and Natural Soundscape

There is an increasing body of research into acoustics for wellbeing and various related applications, linked to biophilic design, 'reconnection with nature', and regenerative standards, such as the Well Build, Living Building Challenge and Build with Nature. In those applications, positive sounds are used to enhance wellbeing within the environment, and to improve wellbeing and productivity.

In addition, natural psychoacoustics are used to mask unwanted, disruptive noises that promote adverse responses that can range from minor inconvenience to extreme stress impact. Terrapin Bright Green [Browning, 2018] reported that it takes 23 minutes to re-engage with a task once disrupted by unwanted noise, and both passive and natural sounds can be introduced in the workplace to reduce impact, whilst boosting wellbeing satisfaction. In one study, self-reported time wasted decreased by more than 55% following the installation of an active acoustic treatment system [Hongisto, 2008].

There is however a nuanced aspect to using natural sound as acoustic masking. The sounds that are introduced have to be appropriate and local. Non-native bird soundscapes were reported to be a distraction in Cundall's Well Build Standard biophilic office in Birmingham, unlike the welcomed soundscape of local native bird species [Cundall, 2020]. TBG made a similar point, stating that "water pouring into a basin has the highest acoustic masking characteristics, from a psychoacoustic standpoint, it is not as effective as water naturally flowing like a stream or small waterfall"

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2.5 ANNEX 1: TOPICS FEATURING A REGENERATIVE INDOOR ENVIRONMENT

2.5.1 AIR QUALITY

Formaldehyde [United States Environmental Protection Agency (EPA), s.d.]
Formaldehyde is a colourless and potentially flammable gas at room temperature. Exposure to this hazardous chemical may cause adverse health effects e.g., irritation of the skin, eyes, nose and throat. Continuous exposure to high levels of formaldehyde may also cause some types of cancers. The primary way a person can be exposed is by breathing air containing off-gassed formaldehyde. Everyone will be exposed to small amounts of airborne formaldehyde that has off-gassed from products. In buildings, it is mainly found in:

- resins used in the manufacture of composite wood products (i.e., hardwood plywood, particleboard, and medium-density fibre-board);
- building materials and insulation;
- household products such as glues, permanent press fabrics, paints and coatings, lacquers and finishes, and paper products.

Particulate matter: PM_{10} / $PM_{2.5}$ [United States Environmental Protection Agency (EPA). available online].

PM_{10} particles are smaller than 10 micrometres in diameter. High levels of PM_{10} particles in the air can irritate the eyes and throat. People with existing heart or lung conditions, e.g., asthma and other respiratory issues, can experience an increase in symptoms, including wheezing, chest tightness and breathing difficulties.
PM_{10} particles can commonly be produced by sea salt, pollen and combustion activities, such as motor vehicles and industrial processes., but also mainly by unsealed roads.
At another scale, $PM_{2.5}$ particles are smaller than 2.5 micrometres in diameter. Tiny $PM_{2.5}$ particles can be inhaled deeply into the lungs, and can therefore cause adverse health effects especially in children, people over 65, pregnant women and people with existing heart or lung conditions. Symptoms may include wheezing, chest tightness and breathing difficulties. $PM_{2.5}$ particles result from the burning of fossil fuels, organic matter and most other materials, such as rubber and plastic. Motor vehicles, power plant emissions and bushfires are all major sources of fine particles.

2.5.2 HYGRO-THERMAL ENVIRONMENT

ANSI/ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy [ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2013]
Indoor environments must be compliant with thermal comfort methods proposed in ANSI/ASHRAE Standard 55, in accordance with the type of environment and heating/cooling/ventilation systems. In particular, for mechanically ventilated buildings and elevated air speed, the use of the SET method is suggested.
Standard Effective Temperature (SET): the temperature of a hypothetical environment at 50% RH, <0.1 m s-1 (20 fpm), average air speed (Va), and mean tr = ta, in which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo will be equivalent to the heat loss from a fully clothed person in the actual environment with a normal level of activity.

2.5.3 VISUAL ENVIRONMENT

Useful Daylight Illuminance (UDI) [Nabil and Mardaljevic, 2005].
Derived from a climate-based daylighting method, UDI is defined as the annual occurrence [%] of illuminances across the work plane where all the illuminances are within the range 100-2000 lux.
Equivalent Melanopic Lux (EML) [International Well Building Institute (IWBI), 2019]. Equivalent Melanopic Lux is a measure of light used to quantify the melanopsin-encoded response to the stimulation of a light source, obtained through calculations using data on the light output of the lamp, the visual light and the melanopic spectral analysis curves, as well as the response to light.

2.5.4 ACOUSTIC ENVIRONMENT

Noise criteria (NC) [International Well Building Institute (IWBI), 2019]. Noise criteria is a rating method for indoor noise from equipment and similar. The method is based on a measurement of sound pressure levels and a set of sound pressure criteria curves of the octave band spectra ranging from 63-8000 Hz. The criteria curves define the limits of the octave band spectra that must not be exceeded to meet the occupant acceptancy levels within the actual spaces.

2.5.5 HUMAN VALUES

% with windows access/daylight [International Well Building Institute (IWBI), 2019].
Access to daylight and external views has been proven [California Energy Commission, 2003] to boost mood and productivity within indoor office environments. This measure reflects the percentage of all workstations at a given distance from an atrium or a window with views to the exterior.
Visual connection to nature [Orians and Heerwagen, 1992]

Visual preference research indicates that the preferred view is looking down a slope to a scene that includes copses of trees casting shade, flowering plants, calm non-threatening animals, indications of human habitation, and bodies of clean water. It can be measured by means of a view factor from the workstation.

2.5.6 OCCUPANT RESPONSES

% satisfied people
Occupant responses are described as the percentage of people satisfied with each of the four main comfort areas, i.e.: indoor air quality, hygro-thermal environment, visual environment and acoustics. It can be assessed by administering subjective survey questionnaires to building users.

3 THE IMPACT OF CLIMATE AND SOCIO-CULTURAL ELEMENTS ON REGENERATIVE PARAMETERS AND USER EXPECTATIONS

AUTHORS

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CONTENT

3.1 INTRODUCTION

The use of technology in construction can be said to have significantly improved comfort and the construction of energy-efficient buildings. Prior to the development of complex indoor air-conditioning technologies – Heating, Ventilation, and Air-Conditioning (HVAC)-, buildings had essentially to be built in close alignment with the location and the regional climate, using locally available building materials and construction techniques, and constructed within the social context of everyday usage. Today, we have increasingly moved away from this awareness, both with our knowledge and with our craft. Buildings can be constructed according to any comfort standards, regardless of external climatic conditions and regional location factors, purely through technological solutions.

On average, people spend 80% to 90% of their life indoors. Likewise, buildings consume around 70% of final energy through HVAC systems and artificial lighting. “The high energy consumption of air-conditioning is largely due to the uniform control of indoor temperature regardless of the building’s location, yet as demonstrated in the literature, it is not really necessary to ensure thermal comfort” [Rupp, Vásquez, and Lamberts, 2015].

Nevertheless, the indoor climate is perceived individually and the requirements are subjectively shaped. Various studies have shown different preferences for a comfortable indoor climate according to the origin, climate, socio-cultural context and individually subjective criteria. In particular, thermal comfort not only depends on physical parameters. “The human body’s physiological and psychological responses to the environment are dynamic and integrate various physical phenomena that interact with space (light, noise, vibration, temperature, humidity, and so on)” [Rupp, Vásquez, and Lamberts, 2015].

While a number of definitions of sustainability are currently used, they may convey the notion of a state in which humankind lives within the carrying capacity of the Earth [Gibberd, 2003]. Therefore, any discussion of sustainability embraces the ongoing relationship between human and natural systems. For example, the conceptual underpinnings of the Millennium Ecosystem Assessment is that people are integral parts of ecosystems and that a dynamic interaction, prompted by changes in the human condition, operates between them and parts of other ecosystems, driving changes within ecosystems, both directly and indirectly, and thereby causing changes in human wellbeing [Cole, 2012].

3.2 DEFINITIONS: REGENERATIVE USER BEHAVIOUR

The understanding of the interconnection between user expectations, including regenerative elements and climatic, cultural and social factors is based on defining the system of *user behaviour*.

According to the purposes of behavioural research, the definitions of user behaviour may be organized into three major groups:

- *Economic definitions*: based on the overall attendance of the individuals involved in an economic decision, business economic case, and overall economic process. Within each definition, individuals are treated as stakeholders, each having individual and/or group needs. Examples of this approach are the Triple helix model of innovation and the Stakeholder model in economics;
- *Social definitions*: based on the behaviouristic approach to the behaviour of individuals among certain group(s). Knowledge of individual and/or group behaviour is therefore treated as an instrument for response management, with respect to individual and/or group manipulation. Examples of this approach are: leadership models, motivational approaches, marketing approaches to customer management, and so on;
- *Psychological definitions*: based on the biological processes that cause individuals to react to different changes in physiological processes and to external psychological and biological environments. An example of this approach is the model of the psychological reaction of the individuals.

In addition, much broader definitions of user behaviour may be found in mathematical or computer-based approaches. For example, a simple search of indexed publications on the Scopus database, using the search term “user behaviour”, found that almost 40% were connected to medicine, 27% to mathematics and computer sciences, fewer than 20% covered social approaches, and fewer than 10% referred to environmental approaches (Figure 4).

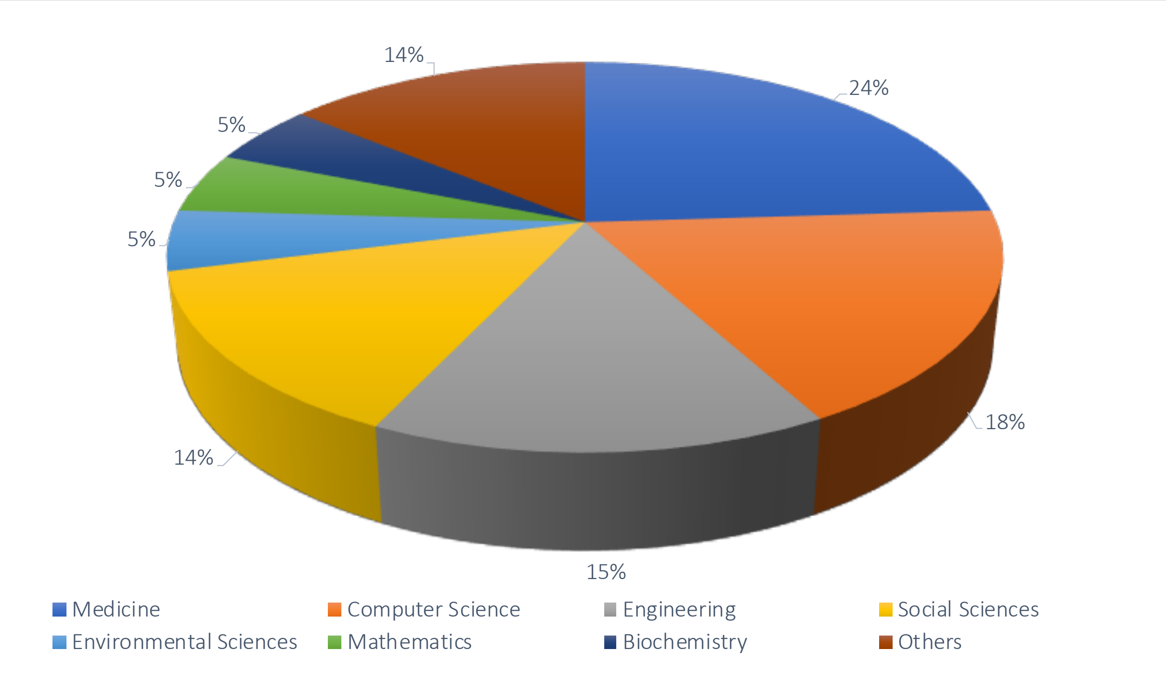

Figure 4. Share of publications concerning user behaviour

As the interconnection under investigation covers social, cultural and climate factors, the most significant model is a social behavioural model. The very first individual model for social behaviour was advanced, in the 1940s, and was later developed through a behaviouristic social approach, in the 1960s. The model explains the system approach and consists of two nodes/ports: *input* and *output*. The input port receives the combination of different influences that could vary and the output port concerns the results that are found (Figure 5).

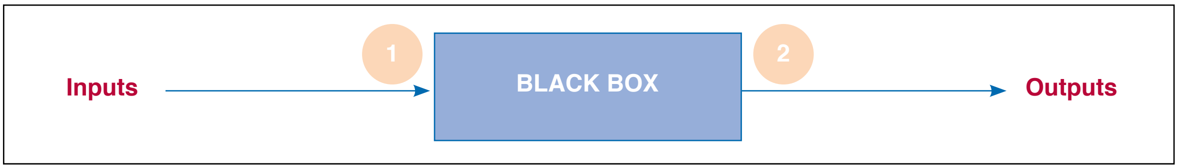

Figure 5. Black box behaviouristic model

The development of the cognitive social behavioural model needs a strict definition of the input elements that predict the output results. Thus, two main characteristics of social behaviour are added, which measure:

1. The degree of acceptance of the input factors by the items of the learning model (e.g., learning machines model) and the acceptance model (e.g., Innovation diffusion model).
2. The way the individual is affected by the items of the knowledge-sharing model (e.g., knowledge-distribution model) and the satisfaction model (e.g., Expectation Confirmation Model)?

Although all the above examples have been well described and could build additional points to understand the impact of social and cultural factors on regenerative user behaviour, the most significant model is the Expectation Confirmation Model (ECM).

The ECM consists of 4 major elements: individual perceptions, confirmation, satisfaction, and intention (Figure 6).

Figure 6. Expectation Confirmation Model (ECM)

Confirmation: defined as “a rational BELIEF”, it explains the extent to which consumer expectations with regard to use “were met in reality, and refers to this evaluation process” [Bhattacherjee, 2001; Hozhbari at al. 2014].
Perception: considered as the sum of basic utilitarian factors in relation to consumer intention. Thus, it is the process of either attaining AWARENESS or UNDERSTANDING sensory information. So, perception is experiencing the world, categorizing it and interpreting it [Qiong 2017].
Satisfaction: a JUDGMENT of pleasurable levels of consumption-related fulfilment including levels of under-fulfilment or over-fulfilment [Arnorld, Price and Zinkha, 2004]. Thus, satisfaction is covered by the feeling that emanates the fulfilment of individual needs and wants. In many cases, satisfaction is explained as both an emotional and a cognitive RESPONSE to different influences.
Intention: found as goal states in the EXPECTANCY value, it is the result of a process that takes time, requires some deliberation and focuses on consequences [Loewenstein, Weber, Hsee, and Welch, 2001].
The general ECM had been applied in different social, economic, and behavioural research projects. However, the regenerative elements of the model have been discussed in very few papers. Some improvements to the ECM for regenerative needs have been proposed by (Liao, Su, Huang, and Shadiev [2019], among which the predictors that impact on the personal intention to participate in air quality control and air pollution prevention. Some of the factors of the ethical consumerism behavioural model are comfortable individual lifestyles; consumer habits; individual attention to the environment
According to Liao, Su, Huang, and Shadiev [2019] “only, when consumers are faced with dangers threatening their own life (such as threats of climate change) would they begin to care about their rights, change their perception, thoughts, and attitudes, and further urge themselves to adjust their daily life and consuming habits.” Therefore, the general ECM could be improved (Figure 7).

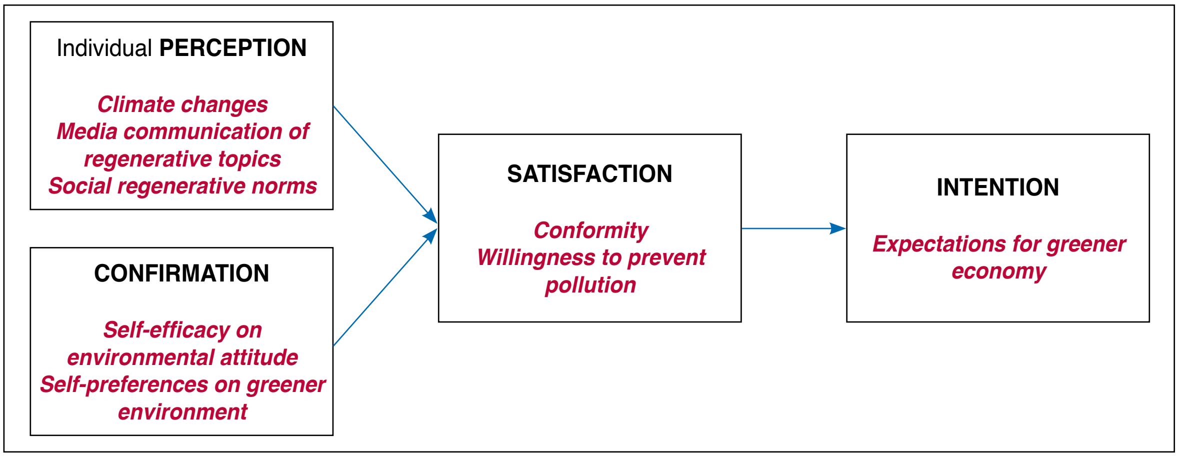

Figure 7. Regenerative Expectation Confirmation Model (ECM)

The elements of regenerative social behaviour among individuals can explain the impact of climatic, cultural, and social factors on overall regenerative behaviour. They have been discussed in a range of papers, among which the following represent some examples:

- Satish [2019] exams the relationship between the cultural values of users and energy consumption. Furthermore, Satish [2019] found that the notion of comfort, reflecting individual preferences and internal ambiance, energizes building inhabitants and brings pleasure, while saving on energy in the process. The core of his research has integrated the PERCEPTION of thermal comfort.
- Kiil, Mikola, Thalfeldt and Kurnitsk [2019] found some additional perception and confirmation-related factors that predict individual satisfaction and refer to expected productivity and energy consumption. According to their research, two main factors -comfort and productivity- affect health, and directly influence the energy use of the building: thermal comfort (TC) and air velocity (AV). Thus, they stated that: controlling thermal indoor climate and avoiding the risk of draughts are among the key factors for ensuring employee satisfaction.
- So, properly designed and functioning technical systems will help to ensure productivity, wellbeing and comfort. In addition, Calì *et al. [*2019] based on Kim S. and Cho B. [2013] and Satish *et al. [*2012] found that comfort conditions and good air quality, all year round, are significant for the productivity of the occupants located within a room.
- Santi, Leporelli and Di Sivo [2019] developed the links between architecture and public health and how urban design can positively influence the latter. They proposed the model shown below in (Figure 8).

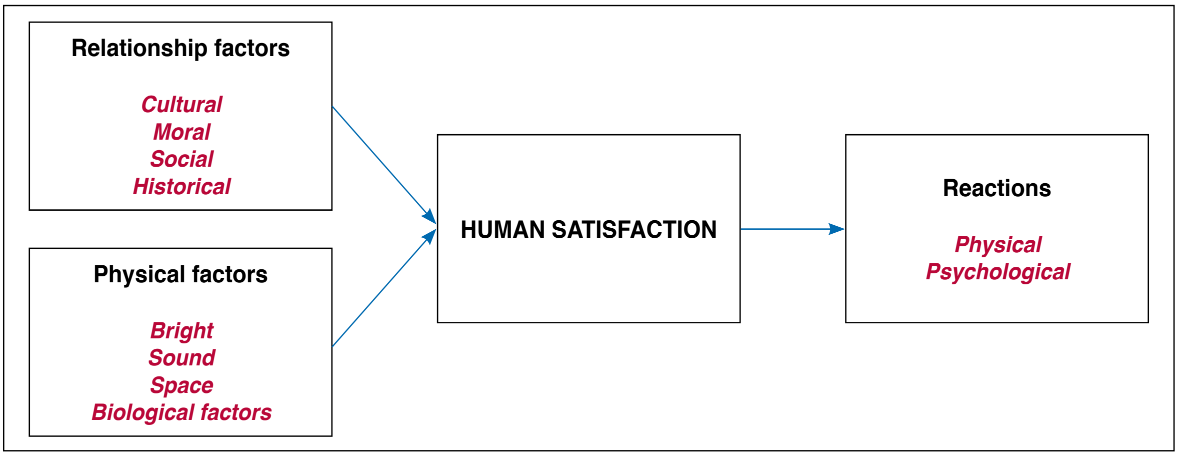

Figure 8. Model of Sustainability in Architecture

In conclusion, the regenerative parameters and the expectations of users are entirely dependent on both the climate and the socio-cultural elements of the immediate environment in which the individual is living. There is a strong relationship between some climate elements, such as thermal comfort and air velocity, which can satisfy user expectations. Likewise, architectural space, brightness, and numbers of room occupants act as social perception factors that affect individual satisfaction levels and refer to the physiological and physical reactions of humans that are dependent on energy consumption.

3.3 THE ROLE OF CULTURE AND LOCAL CONTEXT IN UNDERSTANDING TECHNOLOGY AND COMFORT

The transfer and acceptance of technologies and techniques have to be based on sound knowledge of a regional culture. It must be recognized that the existing building stock forms an essential aspect of regional diversity and culture. A European approach is based on strong public policies, the importance of public service and active state intervention, especially in the realms of the built environment, 'green' issues and cultural heritage [Kohler, 2003].

3.3.1 CULTURAL ISSUES AND EXPECTATIONS

There is a prevailing consensus that information, technologies, and practices are often compromised when imported into another region or country. In addition, strategies and technologies that differ from user expectations usually compromise the goal of creating an environmentally progressive building. The challenge for professionals dealing with this issue is how to manage social and cultural change, in order to provide levels of comfort that are more environmentally friendly.

Recent research shows that one of the most important limiting factors is the inability to articulate and to understand the contexts of local expectations and both social and cultural values, as well as lifestyle. "The built environment can be characterized as the embodiment of human values and ingenuity, as represented by the knowledge and priorities of its creators. Further, the acquisition and assimilation of the knowledge to create the built environment are clearly shaped by a broad range of contextual issues" [Cole and Lorch, 2003].

Cole and Lorch [2003] criticized the supply side of the construction industry for transferring 'foreign' technologies and design standards across regional and cultural boundaries without understanding local contexts. According to those authors, a key factor in the success of green building practices is the development of supply side capabilities that can adapt global information to local cultural expectations, habits and patterns of living, coupled with local climatic conditions, materials and technologies. Evidence suggests that confronted by green buildings, occupants may make changes to adjust them to more conventional expectations, thereby reversing their intended environmental benefits. Ensuring the success of green buildings may require a transitional period that will enable users to undertake the necessary learning, both for reassessment and for adjustment to different conditions. [Cole and Lorch, 2003].

A building designed with excellent 'green' performance standards can be severely compromised, because its specifications and technical performance fail to account in an adequate way for the needs of the inhabitants, their expectations, and their behaviour. Moreover, long-term, broadly based solutions to environmental problems will depend on significant changes to both human values and actions [Cole and Lorch, 2003].

A series of case-studies within the UK, known as the Post-Occupancy Review of Buildings and their Engineering (PROBE) has provided feedback on the performance of many buildings, which have been the subject of copious academic study. They illustrate the differences between anticipated and actual performance [Cohen et al., 2001]. In particular, they show that the actual performance of buildings is compromised by the complexity of the systems built into them. A key lesson is, therefore, that the environmental success of a building depends on *matching technological and management sophistication*.

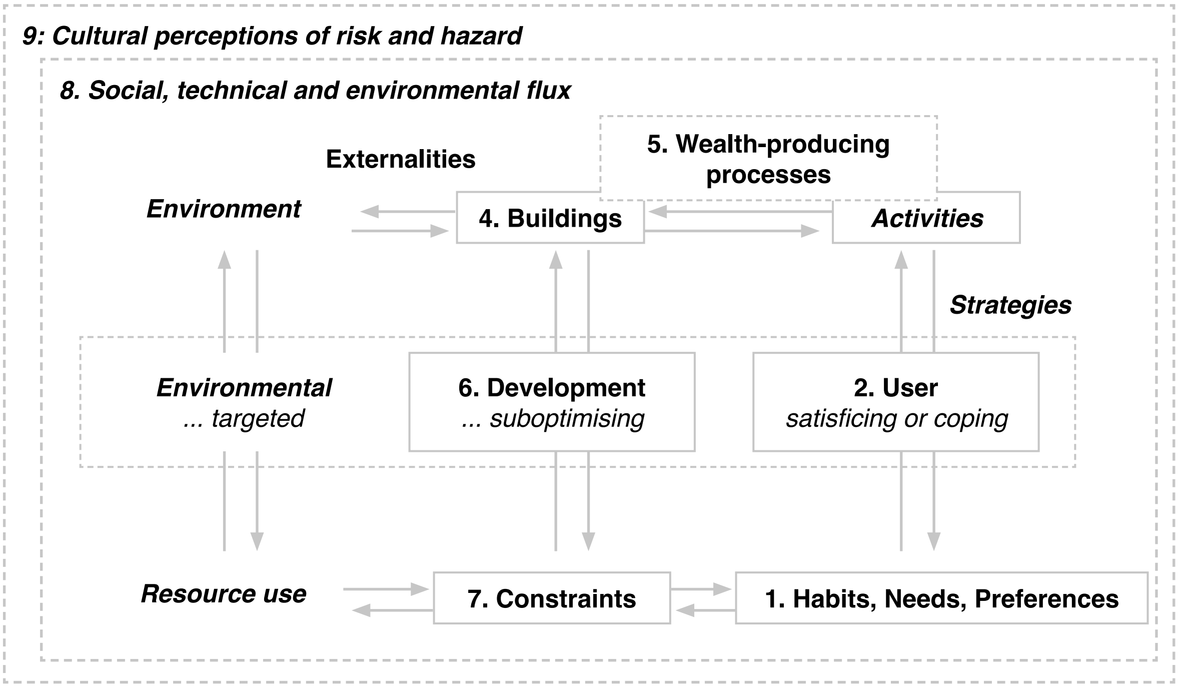

Figure 9. The complexity of buildings as total systems – the user perspective[2]. Source: Leaman [2003], p. 155

Habits, needs, and preferences are to some extent culturally dependent. They are affected by attitudes to health, safety, risk, and fashion, as well as regulations and organizational and social norms. In recent years, for example, expectations towards building-related health have been rising rapidly, so conditions which were tolerated a decade ago are now unacceptable.

As Figure 9 shows, user needs and preferences are linked to user strategies, which are in turn connected to (3) *activities* (the collective tasks that are being carried out in buildings – office, health, educational, and so on) that are carried out within (4) buildings, which contribute to (5) *wealth-producing* processes. Buildings themselves are created by a completely different set of decision-making processes to those used by normal occupants, represented as (6) *development strategies*. These strategies operate within (7) *constraints* (e.g., the existing physical infrastructure, planning law, and investment market, as well as time, cost and quality criteria). Development strategies gain utility by seeking out perceived benefits within the boundaries of the perceived constraints. This is summarized in Figure 9 as 'sub-optimizing'. To complete the picture, everything connected in boxes 1–7 operates within a background of (8) *social, technical and environmental flux* (the volatility of underlying change), and (9) cultural perceptions of risk and hazard (the effect of local cultures on perceptions and behaviours)[1.]

Social, technical, and environmental flux represents the volatility of change, including innovation, government regulation, physical change, social mores and political systems, all of which can, but often in unpredictable ways, affect buildings and their use. Some contextual aspects assume global importance, namely climate change and energy efficiency, and others, especially national regulations, can be equally significant in their way.

Figure 10 considers the context from the perspective of a designer. 'Context-free' refers to principles, rules and processes that, irrespective of context, may be applied anywhere. 'Context-dependent' are locally determined factors. The four quadrants in the following figure refer to four design strategies:

2 Satisticing denotes a decision-making heuristic strategy involving a search through available alternatives for a threshold that is considered acceptable. A combination of satisfy and suffice, the term was first coined by Herbert A. Simon, in 1947, in ‚Administrative Behavior: a Study of Decision-Making Processes in Administrative Organization (1st ed.) New York: Macmillan'.

- Make invisible – those things that are supposed to work only in the background with little or no human intervention.
- Make usable – things needing regular attention and/or interaction. Importantly, this is linked to management culture and occupant convenience.
- Make habitual – formal and informal rules that help with safe, comfortable, and smooth running, which is more a matter for individuals.
- Make acceptable – things which are not prescribed and covered by the rules, but allow scope for individuality, innovation, and change.

The best buildings tend to perform well in all four quadrants. For example, buildings that can properly be said to be flexible and adaptable will have included consideration of all four strategies. They include issues such as usability, innovation, habit (i.e., cultural norms in the organization and user etiquette), safety, security, risk, value and uncertainty.

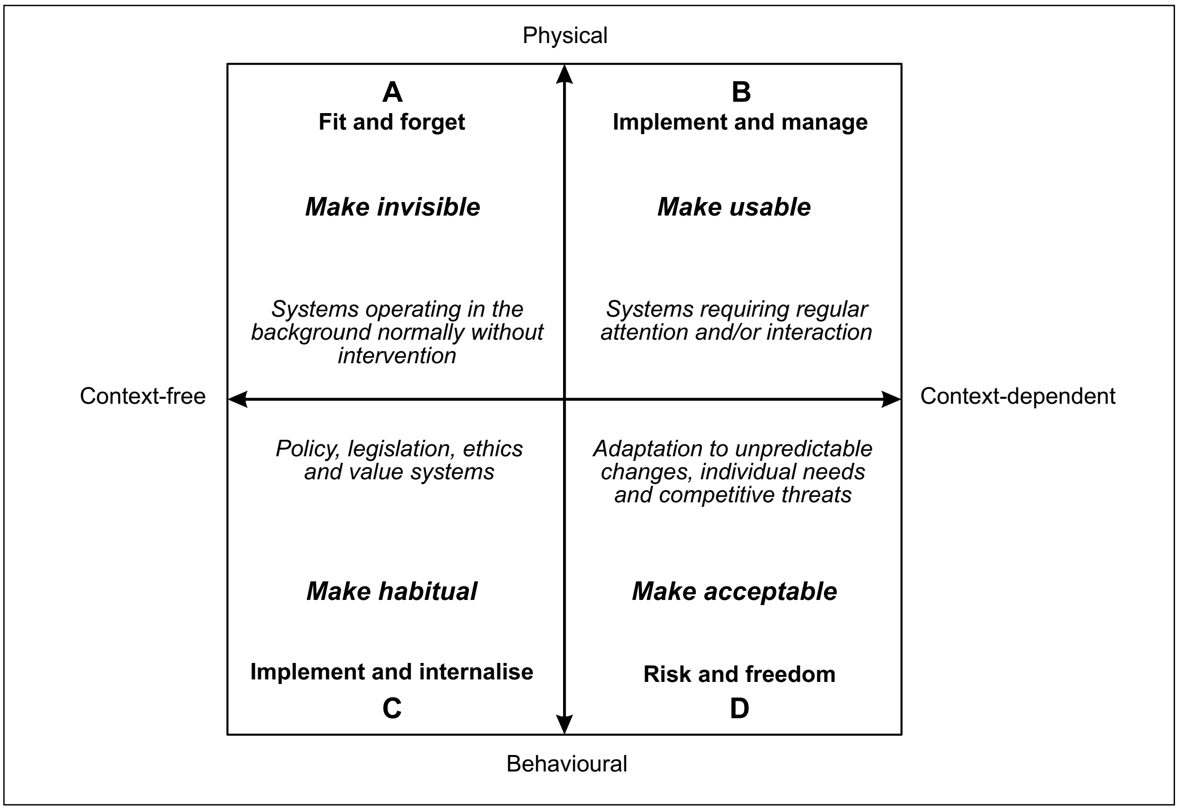

Figure 10. Source: Leaman [2003], p. 160

3.3.2 REVISITING THE DEFINITION OF COMFORT

What is comfort and why is it important to examine it? The answer is complex and will vary widely when viewed from such various disciplines as engineering, physiology, psychology, social science, and cultural anthropology. The notion of comfort has evolved throughout history, responding to various social, technological, economic, and cultural influences. Historically, the very word 'comfortable' has taken on a range of meanings. It was not until the nineteenth century that the term was first used to refer to environmental comfort related to light, heat and ventilation [Rybczynski, 1986]. Today the term 'comfort' relates to a physical and, in particular, a thermal state of wellbeing and satisfaction. The historical notion of 'sufficient' is still present, particularly within the engineering view of comfort.

This approach ignores the complexity of comfort and all of its contextual and cultural influences, while the simple goal of creating 'thermal neutrality' in buildings hinders the possibility of creating indoor environments that are richer in their experiential qualities than neutrality and have the ability to provide valuable sensory stimulation.

As Heerwagen [2000] argued, pleasure, comfort, and productivity of building occupants are closely linked to their real and perceived control over interior environmental conditions. These insights are essential for creating the guidelines that are comprehensible, simple to manage and use, and that provide quick responses to user-induced change.

In reaction to conventional notions of comfort, it has been suggested that the "future of comfort remains fluid, contested and controversial and that the range of possible responses is much wider than that currently contemplated by energy and environmental policy-makers" [Chappells and Shove, 2005].

It is interesting to observe the behaviour of the building users in a residential and commercial building. Unlike residential buildings where inhabitants typically have a greater degree of control and can express their comfort needs and desires by adapting their indoor environment more readily, inhabitants of commercial buildings rarely experience extensive control over their environment. Moreover, inhabitants of commercial buildings, who may feel a greater sense of control, may also experience a greater sense of comfort. It is widely understood that comfort provisioning and experienced comfort are context dependent [Cooper, 1998; Crowley, 2001; Ackerman, 2002].

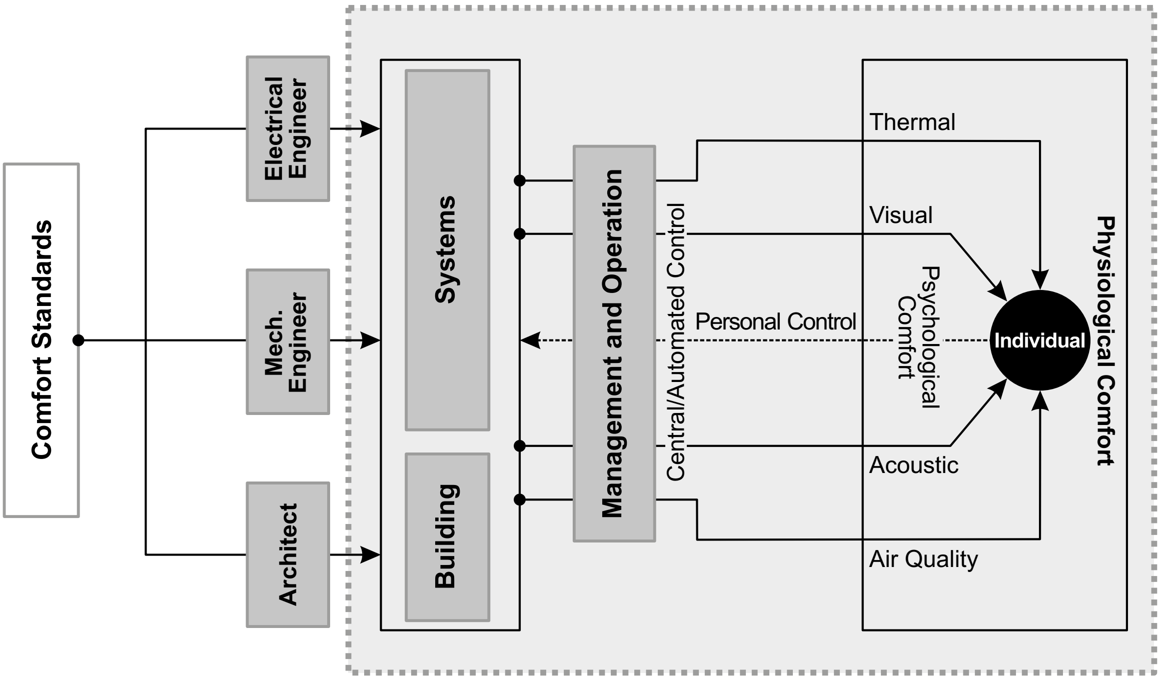

Figure 11. Conventional approach to comfort provisioning. Source: Cole et al. [2008].

Figure 11 shows the approach to comfort provisioning in conventional building design practice where the emphasis is on mechanical and electrical systems and where consultants operate independently from one another. The scope, emphasis, and requirements that are deemed appropriate for 'comfort' are represented in standards applicable to specific building types and usage. The critical dimensions of comfort – thermal, visual, acoustic and air quality – are primarily described in terms of an individual's physiological and (limited) psychological comfort. These comfort standards serve as a guide for design consultants, and later as a reference for regulatory authorities to assess whether 'acceptable' conditions have been provided within the workplace.

Comfort standards will be variously interpreted by the respective design professionals in the context of the specific project and the requirements of the client. A more critical issue is the translation of the universal comfort standards through the choice of specific design strategies that individually and collectively create the context for building operators and occupants. As Figure 11 indicates, the process is a linear one, with the occupant's physiological (and more rarely psychological) comfort that is seen as the result of a series of design decisions. There is little opportunity for feedback from the occupant regarding those design decisions, and even less so for the comfort standards. The extent to which psychological needs are met depends on the choice of design and control strategies. Behavioural aspects of comfort are largely ignored, except those that fall under the categories of physiological or psychological, e.g., activity level, clothing, level of personal control. The result is a unidirectional design process where the building occupants are the passive recipients of the outcomes of such research and practice. Several developments have occurred in design and building professions over the past decade that have begun to influence the notion of comfort and comfort provisioning. Green buildings aspire to far superior environmental performance compared with their conventional counterparts. Many green buildings rely on natural conditioning to meet the comfort needs of the inhabitants.

The successful integration of environmental systems and strategies requires transcending professional boundaries and working towards a comprehensive, team-based approach known as an Integrated Design Process (IDP) and IPD. Both IDP and IPD have emerged offering a profoundly different approach to building design than the dictates of linear convention. Building environmental assessment methods, such as Leadership in Energy and Environmental Design [LEED] and the Building Research Establishment Environmental Assessment Method [BREEAM], have institutionalized the need to assess building environmental performance across a broad range of performance metrics, including indoor environmental quality.

Following on from IDP, and incorporating the same values of dialogue and communication, Post-occupancy evaluation (POE – the systematic evaluation of building performance and/or opinion about buildings in use from the perspective of the people who operate and/or inhabit them) has earned increasing attention and application over recent years, particularly when applied to green buildings. It is widely known that building performance in use often differs markedly from the anticipated or predicted behaviour during design. According to a 2007 study by the New Buildings Institute, 30% of LEED buildings performed better than expected, 25% performed worse than expected, and a handful had serious post-occupancy energy consumption problems [Owen et al., 2007]. This performance gap is not so much the results of the building design and the technology themselves, but rather from the differences between assumed and actual patterns of occupancy, the use of controls, and building operation and management.

There is an increasing recognition of the need to move beyond physiological comfort and more considered acknowledgment of users and their engagement with controls and other building environmental features that is sufficient to re-contextualize the notion of comfort. However, before doing so, it is necessary to acknowledge two additional factors: climate change, which adds a sense of urgency, and agency and complexity, which provide a new lens through which to view the challenges ahead. The building sector has been identified as a key potential contributor to efforts to mitigate climate change [Metz et al., 2007; Urge-Vorsatz et al., 2007a, 2007b]. Substantial leaps forward in building performance will be required. These advances will have significant implications for conventional approaches to comfort and, depending on the strategies employed, will provide further impetus to redefine and to broaden the scope of what building inhabitants consider 'comfortable' indoor environments. An integrative and participatory process is one in which the relationships between inhabitants and between inhabitants and building systems are considered as interactive and multidirectional, rather than the linear or predictable assumptions of the conventional approach. Figure 12 illustrates the ways that climate change and agency-and-complexity together form a new lens with which to view emerging design and construction strategies (green building, integrated design POE, and performance assessment) that affect occupant comfort.

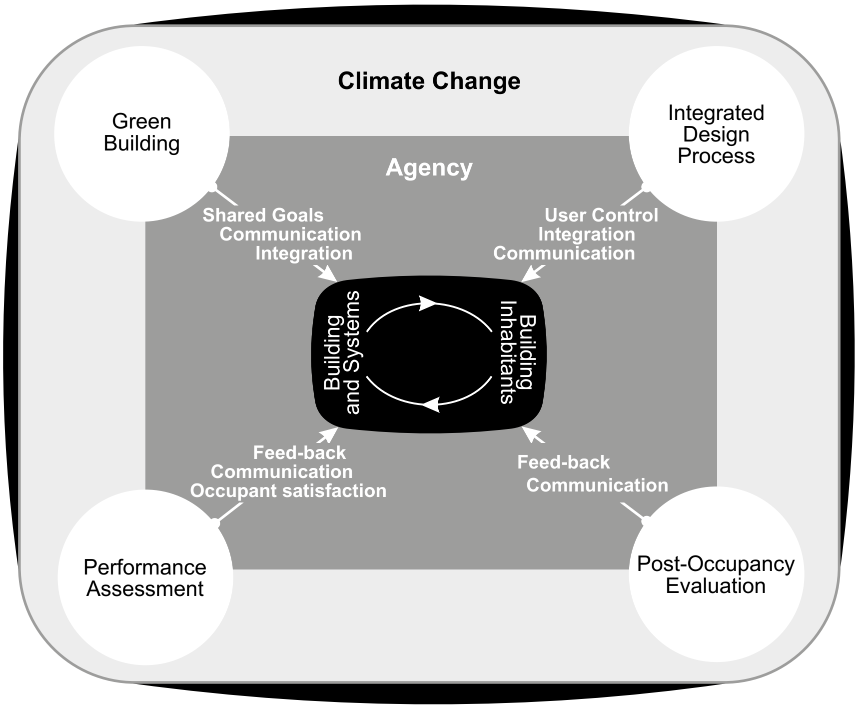

Figure 12. New context for comfort. Source: Cole et al. [2008].

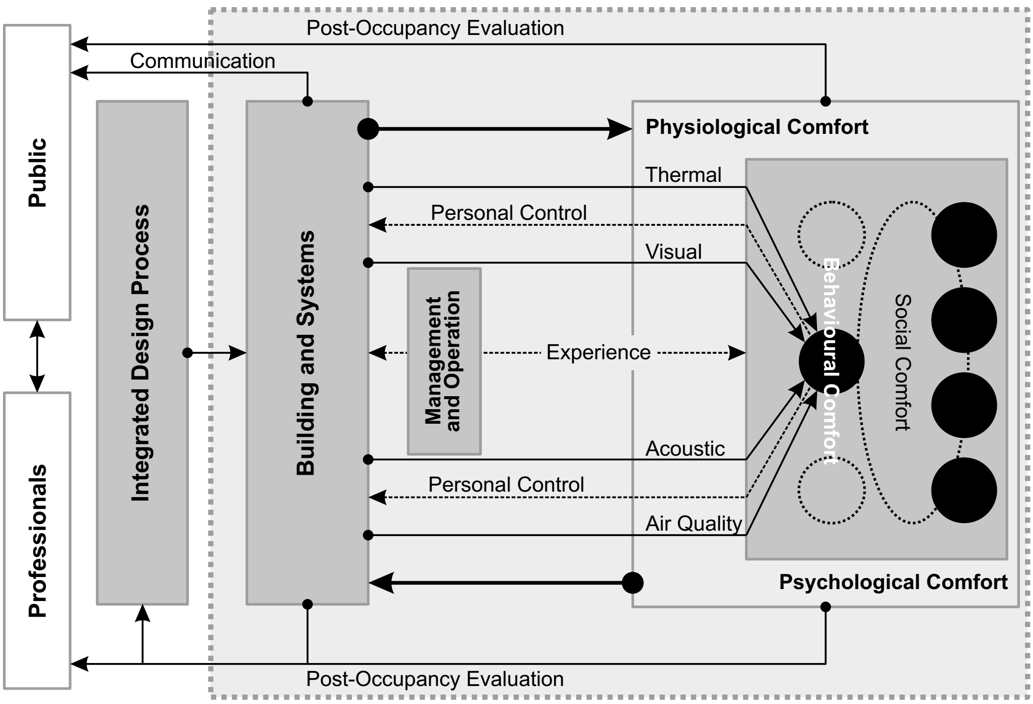

Figure 13. Broader approach for comfort provisioning. Source: Cole et al. [2008]

Figure 13 illustrates the emerging expansion of the notion of comfort. In particular, Figure 12 acknowledges that comfort research and provisioning must make a substantive move beyond physiological comfort, to address the psychological, behavioural, and social (or collective) drivers of inhabitant comfort. In a building

and inhabitant system moving towards interactive adaptivity, those drivers will be valued and will have the necessary flexibility to adapt to the changing needs of the entire system over an extended time.
Social comfort relates to the relationships between inhabitants and includes issues of adjacencies of workplaces and sense of territory, the status associated with open and closed offices, and proximity to windows, privacy and communication, opportunities for interaction, a sense of collective agenda, and so on. Additionally, social comfort refers to the phenomenon of collective understandings of experienced comfort and the co-development of agency for achieving comfort.
These issues have raised a new set of requirements and processes, including feedback, dialogue, communication, and adaptation. In contrast to previous notions of comfort that have centred on individual physiological comfort and that have viewed occupants as passive recipients of a pre-existing set of thermal, luminous, acoustic and air quality conditions, the consequences of these factors support the broadening of the notion of comfort and comfort provisioning, so that it is understood as both bidirectional and interactive.

3.4 OUTDOOR CLIMATE CAN STRONGLY INFLUENCE THE INDOOR ENVIRONMENT!

3.4.1 OUTDOOR CLIMATE AND THERMAL COMFORT

Climate is a defining variable that influences culture, buildings design, and 'human behaviour. [Nicol and Humphreys 2002; Zhang et al., 2017; Luo et al., 2016; Rupp, Vásquez, and Lamberts 2015]. There are several ways that people are affected by the climate, which are in turn related to adapting or responding to the indoor climate.
Zhang *et al. [*2017] compared winter indoor thermal environments, occupant clothing insulation and occupant thermal sensations between South Europe, North America, and Asia. Eight cities from five countries (UK, France, Portugal, Canada and the USA), were chosen for analysis. Although all the cities under study are located in a similar latitudinal range, within a temperate climatic zone, significant differences were evident: “It was observed that the indoor operative temperature and relative humidity varied from regions. European and North American cities had higher temperatures while the temperature of Chinese cities was the lowest. Among the three regions, indoor environments in Europe and China met well with the comfort requirements in their own regional or national standard, while North America had the highest ratio of matching the comfort zones no matter in which standard. Most of the off-comfort-zone conditions in Europe were due to overheating, contrary to those in China that were mainly overcooling. The clothing insulation of the Chinese was the highest and had a wider range. The neutral winter temperatures for Europe, North America and China were 23.4, 22.7 and 21.7 _C, respectively. A comparison between TSV and PMV was made and obvious deviation features were discovered. Europeans tend to feel colder than predicted when the indoor temperature is out of the neutral zone. Chinese TSVs were closer to neutral than they were predicted by PMV, while North Americans showed the opposite result.” [Zhang et al., 2017]; (PMV Predicted mean vote, TSV Thermal sensation vote). The authors concluded that thermal comfort, thermal preferences, thermal acceptance, and occupant thermal sensations varied from country to country. They assumed that “those differences may be caused by different heating equipment, heating policies, cultures, races and other reasons need to be discovered” [Zhang et al., 2017]. Figure 14 shows the long-term trends in wintertime residential temperatures for the UK, the US, Japan and northern China [Luo et al., 2016].

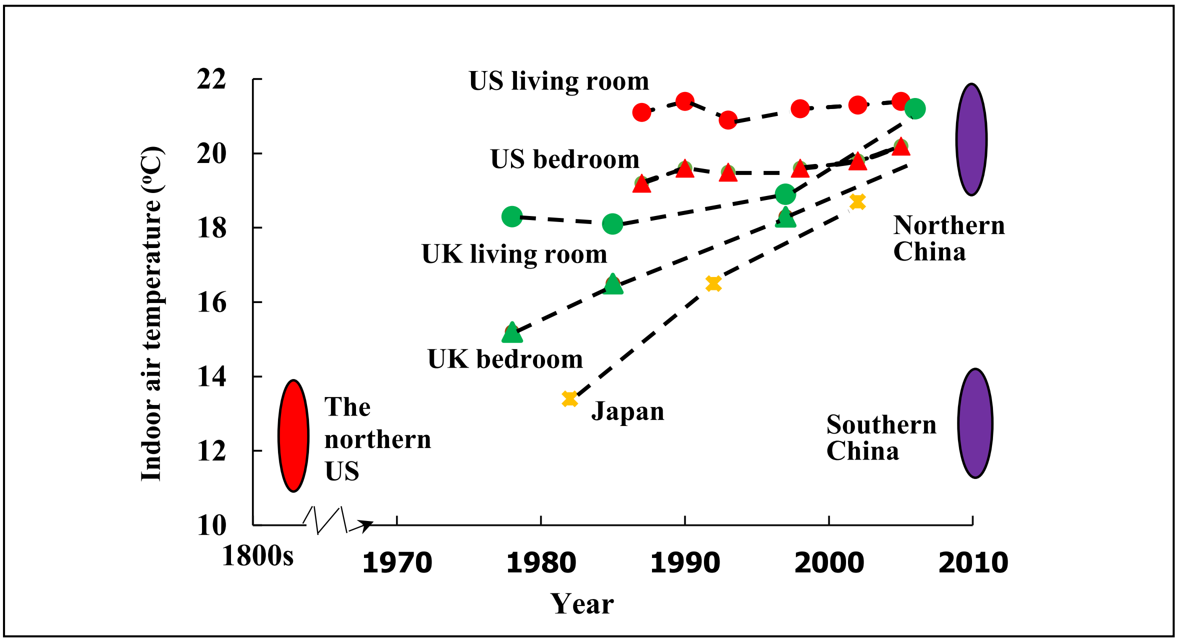

Figure 14. Long-term trends in wintertime residential temperatures in the UK, the US, Japan and northern China. Source: [Luo et al., 2016]

This figure suggests that the different country-specific thermal expectations are converging towards some neutral wintertime residential temperatures of about 21 °C. However, recent studies suggest that there are still significant differences [Zhang et al., 2017; Humphreys, Nicol, and McCartney 2002; Rupp, Vásquez, and Lamberts 2015]. The relationship between outdoor climate and indoor environment is especially seen as a significant factor. Figure 15 [Zhang et al., 2017] shows indoor operative temperature versus outdoor daily mean temperatures in Europe, North America and Asia.

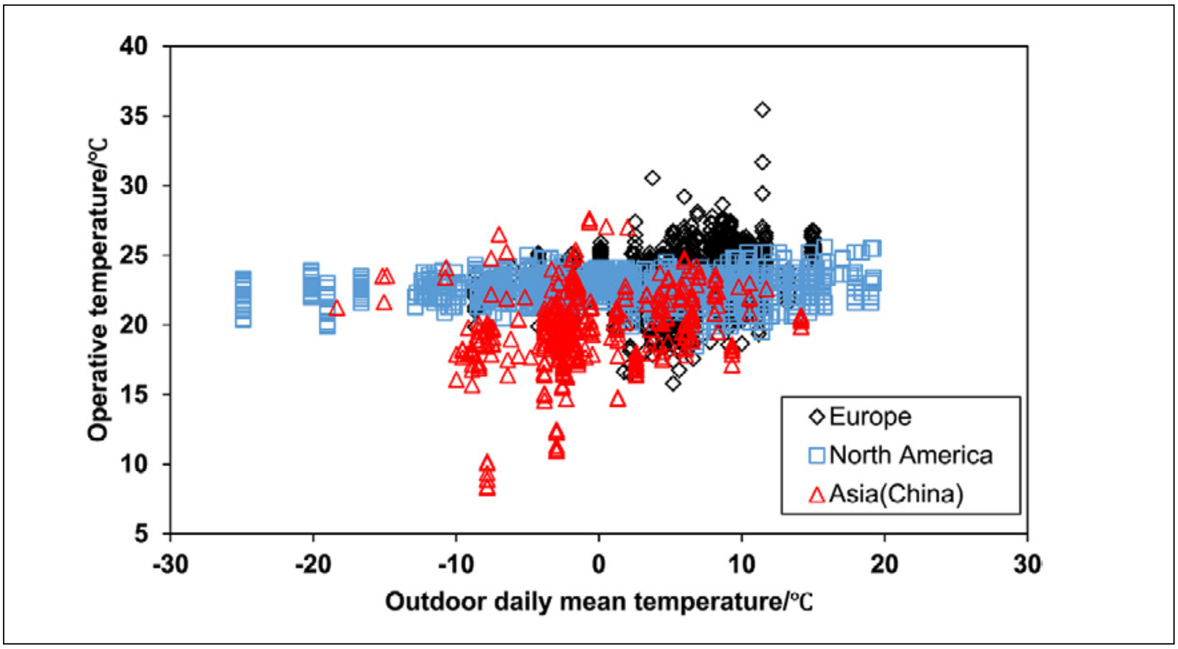

Figure 15. Indoor operative temperature versus outdoor daily mean temperature in three regions. Source: [Zhang et al., 2017]

While indoor temperatures, between 20 °C and 25 °C, are more stable in North America, the data for Europe and Asia show significant differences, depending on the outside temperature. In Europe, indoor operating temperatures often rise above 25 °C, while in Asia they tend to be lower, in some cases under 10 °C. Indoor conditions in North America therefore meet comfort standards more often, while the problem is overheating in Europe and overcooling in Asia. This analysis is, of course, dependent upon evaluating the data as if the standard represented the goal, but we know it has little to do with cultural habits and adaptation.

3.4.2 MUTUAL INTERACTIONS BETWEEN THERMAL COMFORT AND OTHER INDOOR ENVIRONMENTAL QUALITIES

Frequently, comfort criteria are only used to measure thermal comfort for its consideration, but other criteria such as humidity, light and acoustics and their interaction are considered and investigated far less often. Humphreys *et al.* [2002] collected indoor climate data at work-areas in 26 office buildings in five European countries (France, Greece, Portugal, Sweden, United Kingdom) and evaluated the data, specifically in relation to the same issue. The respondents rated air quality, thermal preference and preferred levels of air-movement, humidity, light and sound on a multi-level scale. Over a year, the researchers made more than 4500 such 'desk-visits.' In summary, they found the following subjectively perceived interactions: "The concentration of CO2 had a slight negative relation to the perceived air quality. The relative humidity affected the perceptions, air quality being rated most highly at moderate levels of humidity. The air temperature did not affect the perceived air quality if the respondents were in thermal comfort. When respondents felt too warm, high temperature and humidity had an adverse effect on the perceived air quality. When respondents felt too cool, low temperature and humidity had an adverse effect. These results do not support the view that people prefer the air to be dry and cool, but do support the view that combined high temperature and high humidity have an adverse effect on perceived air quality if people are feeling too warm." [Humphreys, Nicol, and McCartney, 2002] Of particular note is the acknowledged relationship between thermal comfort and the subjectively assessed air quality: "The respondents gave the most favourable assessments of air quality when they felt themselves to be in thermal comfort, requiring no change in their perception of warmth, or the dryness of the air, or of its movement." [Humphreys, Nicol, and McCartney, 2002]. In addition, differences between genders and buildings were found, but these were dominated by country-specific differences.

Further studies have confirmed these results that thermal comfort is the most important criteria for improving satisfaction with the indoor environment [Rupp, Vásquez, and Lamberts, 2015; Frontczak and Wargocki, 2011]. Frontczak and Wargocki analyzed nine studies and deduced from seven of them that thermal comfort is significantly more important in terms of satisfaction with the indoor climate: "Thermal comfort is ranked by building occupants to be of greater importance compared with visual and acoustic comfort and good air quality. It also seems to influence to a higher degree the overall satisfaction with the indoor environmental quality compared with the impact of other indoor environmental conditions" [Frontczak and Wargocki, 2011]. Outcomes from the literature, therefore, suggest giving thermal comfort a particular priority over other indoor factors.

3.5 SOCIO-CULTURAL ASPECTS INFLUENCING REGENERATIVE PARAMETERS AND USER EXPECTATIONS

3.5.1 CULTURAL DIFFERENCES RELATING TO ACCEPTANCE, CLOTHING INSULATION, AND BEHAVIOURAL ADAPTATION

Thermal comfort and indoor climate satisfaction are the results of a balancing process between the physical environment and subjective comfort expectations. Reactions and behaviour are based on experience. Thus, individual requirements and occupant satisfaction are "highly negotiable socio-cultural constructs" [Luo et al., 2016; Chappells and Shove 2005].

A relationship between the perceived air quality and the country of origin was described by Humphreys, Nicol, and McCartney [2002]: "The country of origin was found to dominate the perception of air quality. The next most important was the respondents' subjective thermal state. Least important was the thermal environment itself." [Humphreys, Nicol, and McCartney, 2002]. These differences by country of origin are also dominant in other contexts: "While there were differences attributable to the different buildings, to their mode of operation, to the sex of the respondents, and their interpretation of the scale, these were dwarfed by the differences among the countries."[Humphreys, Nicol, and McCartney, 2002].

Zhang *et al. [*2017] noted cultural differences with respect to the acceptance of different indoor conditions. For example, China has a very low level of meeting required comfort standards, yet its acceptance is highest in comparison with North America and Europe, which indicates the higher tolerance levels of that country.

The authors listed mainly two reasons for cultural differences: (a) Behaviour adaptation: clothing adjustment, common culturally used adaptation devices (electric blanket, hand warmer, etc.); (b) Long-term adaptation: physiological differences between ethnic and psychological ways of thermal adaptation. Nevertheless, more studies for verification are suggested [Zhang *et al.*, 2017].

Clothing insulation, and in particular traditionally and culturally influenced habits with regard to clothing, can be expected to influence perceived interior comfort. For example, Zhang *et al.* [2017] showed that the quality of insulation through clothing is much higher in Asia/China than in North America and Europe. It results in a much higher acceptance of temperatures under common comfort standards. In addition, he also provided a physiological explanation. "On the basis of heat balance, lower indoor temperature leads to more human body heat loss, which makes the Chinese wear more clothes to keep warm. Besides, many studies reported that Chinese/Asians have lower basal metabolic rates than westerners/whites [Wouters-Adriaens and Westerterp, 2008; Qi et al., 2014]. According to the [Predicted Mean Vote] PMV function, people with lower metabolic rates need to wear more clothes feel neutral under the same thermal environment. The clothing insulation of Chinese was the highest and had a wider range" [Zhang et al., 2017].

3.5.2 GENDER DIFFERENCES RELATING TO THERMAL COMFORT AND THE PERCEPTION OF INDOOR ENVIRONMENTAL QUALITY

Women and men rate environmental conditions differently [Frontczak and Wargocki 2011; Rupp, Vásquez, and Lamberts 2015; Karjalainen, 2007]. Studies in controlled environments have been performed to examine gender differences. A literature review carried out by Rupp *et al. [*2015] summed up the following results: "Women are more sensitive to temperature (mainly cool) [Lan et al., 2008; Chow et al., 2010] and less sensitive to humidity than men [Lan et al., 2008] and feel more uncomfortable and dissatisfied compared to males [Schellen et al., 2012]. Women have a lower skin temperature than men [Lan et al., 2008; Schellen et al., 2012]. Men prefer a slightly cooler environment and women prefer slightly warmer conditions [Lan et al., 2008; Chow et al., 2010], despite presenting similar neutral temperatures and no difference in thermal sensation near neutral conditions [Lan et al., 2008]. In another study in a climate chamber, the effect of variation of temperature with height in skin temperature and thermal discomfort was more significant in women than in men [Hashiguchi, Feng, and Tochihara, 2010]. Still, another study showed that in women, the overall thermal comfort sensation is significantly affected by the temperature of the skin and extremities,

a fact that should be considered in non-uniform environments [Schellen et al., 2013].” [Rupp, Vásquez, and Lamberts 2015].
Similar results were reported in a study by Karjalainen [2007]: “The studies were carried out in Finland and considered everyday thermal environments: homes, offices, and a university. The results show significant gender differences in thermal comfort, temperature preference, and use of thermostats. Females are less satisfied with room temperatures than males, prefer higher room temperatures than males, and feel both uncomfortably cold and uncomfortably hot more often than males. Although females are more critical of their thermal environments, males use thermostats in households more often than females.” [Karjalainen, 2007]
Statistically, the women had a different perception of the thermal environment than man, so they are more sensitive to the low temperatures than a man in cold conditions, with a preference for a warmer environment [21–23]. [Silva, Maas, Souza, and Gomes, 2017].

3.5.3 THERMAL COMFORT AND PRODUCTIVITY

The relationship between thermal comfort, productivity, and the presence of plants has so far only been the subject of a few studies. In an office building in the Netherlands, this relationship was explored and the researchers found that the employees felt thermally more comfortable when there were plants in the room [Mangone, Kurvers, and Luscuere, 2014].
A literature review highlights eight physical factors that affect Indoor Environmental Quality (IEQ) and occupant productivity: “Thermal comfort, indoor air quality, office layout, and noise and acoustics were found to be highly significant in affecting occupant productivity. A broad range of case studies and the literature indicate a high correlation between these factors and occupant productivity. There are interactions and correlations between these IEQ factors as well. The review suggests clear interaction between daylighting and thermal comfort, thermal comfort and indoor air quality, ‘look and feel’ and views, and office layout and acoustic properties of an indoor environment.” [Al Horr et al., 2016]. Nevertheless, the authors point out the complexity of defining and achieving comfort: “Occupant comfort is highly subjective and depends on various independent personal variables such as individual metabolism, clothing preference, activity patterns and the localized conditions of different zones inside an office.” [Al Horr et al., 2016].
The variation of thermal environment not only affected thermal comfort but also had a “comparative” impact on the perception of other IEQ factors. When the air temperature deviated from 24°C, the number of dissatisfied people increased with the thermal environment. The thermal dissatisfaction under cool or cold conditions is more significant compared to warm or hot conditions. The variation of thermal environment not only affected occupant thermal comfort but also had a “comparative” impact on the perception of indoor air quality, lighting, and acoustic environment. When the thermal environment was unsatisfactory, it weakened the “comfort expectation” of other IEQ factors, which accordingly resulted in less dissatisfaction with other IEQ factors. Conversely, when thermal environment was quite satisfying, it raised the “comfort expectation” of other IEQ factors, which could retroactively lower the evaluation of the real performance of other IEQ factors. The “comparative” impact of thermal environment on indoor air quality or lighting satisfaction was much stronger than on acoustic satisfaction. Once the quantitative relationship between productivity and the thermal environment had been established, the relative productivity could be predicted based on air temperature, thermal sensation and thermal satisfaction. The optimal productivity was obtained when people felt “neutral” or “slightly cool,” and the increase of thermal satisfaction had a positive effect on productivity. Productivity loss emerged along with thermal discomfort caused by the too high or too low air temperature. [Geng, Ji, Lin, and Zhu, 2017].

3.5.4 ADAPTIVE THERMAL COMFORT, ´RATIONAL‘ INDICES AND WELLBEING

Since thermal comfort is first and foremost subjectively rated and perceived, it would therefore appear logical to consider adaptive and adaptable systems within a certain range.
Current standards are based on a ‘rational’ approach to thermal comfort, and indices are established on the responses of subjects measured under stable conditions in climate chambers. It is concluded from these

results that people in different environmental conditions react similarly to everyday life. However, these values have often not been confirmed in field studies. Nicol and Humphreys [Nicol and Humphreys, 1973] argued that it could be the result of a feedback process within individuals between wellbeing and behaviour that they adapted to the climatic conditions under which the field study was conducted. Accordingly, they proposed an adaptive approach, largely based on field studies in naturally ventilated buildings. "The fundamental assumption of the adaptive approach is expressed by the adaptive principle: if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort." The adaptive approach is based on the natural behaviour of humans to adapt to changing conditions in their environment. "By linking the comfort vote to people´s actions, the adaptive principle links the comfort temperature to the context in which subjects find themselves. The comfort temperature is a result of the interactions between the subjects and the building or other environments they are occupying" [Nicol and Humphreys, 2002]. Thermal comfort stands in the context of three essential variables: first of all, the climate; second, the building with its services; and third, the time in which users respond to changing conditions. They proposed the application of an adaptive algorithm, which calculates variable interior temperatures in each case in relation to the outdoor temperature. Temperature indoors should follow the change in outdoor temperature rather than be kept constant for the entire year and local outdoor climate should be considered.

The adaptive model is based on three inter-related aspects: psychological (comfort expectation and habituation in relation to indoor and outdoor climate), behavioural (including opening windows—which was the most common, and the use of blinds, fans, and doors) and physiological (acclimatization) [Rupp, Vásquez, and Lamberts, 2015]. Nicol and Humphreys [2002] considered that a range of +/- 2 degrees was sufficient to meet individual needs. It is assumed that "… generally, humans avoid discomfort and unpleasant experiences, and hence they are always striving (whether consciously or unconsciously) to change their present state towards a homeostatic state – thus a more neutral or comfortable one. As a result, many of the actions we do are wellbeing-driven: actions that can have effects on both health and comfort. [Ortiz, Kurvers, and Bluyssen, 2017] Accordingly, it should be referred to wellbeing rather than comfort, which also includes health aspects such as stress reduction or health-promoting aspects.

3.6 INFLUENCE OF TECHNOLOGY ON COMFORT CRITERIA

"Based on the available information in CBE's post-occupancy evaluation database (mainly offices), Kim and de Dear [Kim and de Dear, 2012] identified that the type of conditioning (air-conditioning—AC, mixed-mode—MM and natural ventilation—NV) influences the expectation of users with respect to indoor environment quality satisfaction. In NV buildings, good thermal conditions improved overall satisfaction with the working environment (positive effects), while in AC buildings the thermal conditions were associated with negative evaluations in relation to the overall environment [Kim and de Dear, 2012]. In MM buildings, thermal conditions provided both positive and negative impacts [Kim and de Dear, 2012].

Environmental adjustments reflect how occupants interact with the building control systems (i.e. windows, blinds, switches, and other controls). If the building control systems are not operated efficiently, occupants can impact on energy usage when engaging in this thermal discomfort coping mechanism [Azizi, Wilkinson, and Fassman, 2015].

Building design priorities are shaped by the prevailing paradigm and value system of the societal and cultural context within which they emerge. Similarly, the technologies deployed by society reflect its culture and how it understands and engages natural systems. Within this overarching value frame, the ways and extent that environmental issues are emphasized in building design are further influenced by immediate societal concerns in the aftermath of significant events (such as insecurity or economic instability) [Cole, 2012].

Typically, the 'green building' design covers environmental performance issues and human comfort and health requirements at an individual building scale. Several systems expand on the range of performance issues beyond resource use, emissions, and indoor environmental quality. They also have frameworks that organize performance criteria with social, economic and environmental domains to provide a measure of 'sustainable' performance [Cole, 2012].

Green buildings are highly glazed buildings that provide wide access to views of the natural environment outside the buildings and have spacious common spaces that occupants can use as retreats. The different design attributes in the green buildings rather than the conventional buildings are expected to encourage the occupants to exercise healthy adjustments in response to discomfort. The findings extend earlier studies by other authors, by showing that not only can these design features (i.e. spacious common room and access to view the natural environment) reduce occupant stress, but they can also potentially encourage occupants to engage in more personal adjustments. [Azizi, Wilkinson, and Fassman, 2015].

Occupants in green buildings expressed more willingness to suffer discomfort (such as being too hot or too cold) compared to conventional building occupants. Even though the occupants in green buildings have greater access to the control system, they are still less likely to adjust the temperature. It appears that occupants in green buildings are behaving differently in response to their building design. One theory might be that as green building occupants are more aware of the impact that changing temperature and personal heaters can have on energy use, they therefore do not change their building controls. Occupants in the green (TB and OGGB) buildings under study were less likely to adjust the temperature system and chose more personal adjustments, possibly showing that they demonstrate greener behaviour and supporting the notion that green buildings do influence how occupants behave. The comparative study found that occupants in the green buildings engaged in less environmental adjustments, and adopted more personal and psychological coping mechanisms than those occupants in the conventional building [Azizi, Wilkinson, and Fassman, 2015].

One avenue through which the building industry is initiating the application of sustainable development principles in the design, construction, and operation of buildings is in the replacement of traditional technologies with technologies that have a reduced ecological, health and environmental life cycle impact. Technology selection decisions must be based on a clear understanding and proper evaluation of the full range of associated implications and project context, from an environmental, social, economic, and technical perspective (e.g., building type, climatic condition and programmatic requirements). Technology performance in a region, programme or building type may differ from performance in another context [Nelms, Russell, and Lence, 2005].

3.7 ECONOMIC ASPECTS OF REGENERATIVE INDOOR ENVIRONMENT QUALITY

3.7.1 ENERGY POVERTY

Establishment of acceptable, optimal, and healthy indoor environments can be closely correlated with the economic status of population. A significant part of the population in many countries cannot afford to spend even part of the household budget on energy saving appliances. They continue to use old and environmentally unfriendly household equipment that consumes a lot of energy, keeps household costs higher and pollutes the environment. In EU Member States and at a national level, many countries have, over the past 10 years, not only initiated discussions, but also the design and the implementation of measures for energy poverty and the achievement of energy efficiency.

The EU understanding of energy poverty is when a household suffers from a lack of adequate energy services in the home. Adequate warmth, cooling, lighting and the energy to power appliances are essential services needed to guarantee a decent standard of living and citizens' health. Within the European Union, more than 50 million households are classified in the group of energy poverty. The indoor environments of these households are neither acceptable and nor healthy. Simultaneously they cannot afford to modify it in the most appropriate way, in order to meet key indicators. Countries implement different measures to support this part of society. Some of the measures and the policies are focused on energy efficiency, others target energy poverty through subsidies for energy consumption.

3.8 CRITERIA FOR REGENERATIVE INDOOR ENVIRONMENTAL QUALITY

Labuschagne and Brent [2006] concluded that a quantitative social impact assessment method cannot be applied for project and technology life cycle management purposes in the industry at present. It is proposed that social sustainability should be incorporated into both the project and technology life cycle management by means of guidelines and checklists. Labuschagn and Brent [2006] provided the definitions of social criteria shown in Table 9.

Internal Human Resources	**Internal Human Resources focuses on the social responsibility of the company towards its workforce and includes all aspects of employment.**
Employment Stability	The criterion addresses a business initiative's impact on work opportunities within the company, the stability thereof as well as evaluating the fairness of compensation.
Employment Practices	Disciplinary and secrecy practices as well as employee contracts are addressed under this criterion. These are evaluated to ensure that it complies with the laws of the country, international human rights declarations as well as other human rights and fair employment practice standards.
Health & Safety	The criterion focuses on the health and safety of the workforce and evaluates preventive measures as well as the occurrence and handling of health and/or safety incidents.
Capacity Development	The criterion addresses two different, aspects namely research and development, and career development.
External Population	**External Population focuses on the external impacts of the company's operational initiatives on a society, e.g. impacts on the availability of services, community cohesion, economic welfare, etc.**
Human Capital	Human Capital refers to an individual's ability to work in order to generate an income and encompasses aspects such as health, psychological wellbeing, education, training and skills levels. The criterion addresses Health and Education separately.
Productive Capital	Productive capital entails the assets and infrastructure an individual needs in order to maintain a productive life. The criterion measures the strain placed on these assets and infrastructure availability by the business initiative.
Community Capital	This criterion takes into account the effect of an operational initiative on the social and institutional relationships and networks of trust, reciprocity and support as well as the typical characteristics of the community.
Macro Social Performance	**Macro Social Performance focuses on the contribution of an organisation to the environmental and financial performance of a region or nation, e.g. contribution to exports.**
Socio-Economic Performance	This criterion addresses the external economic impact of the company's business initiatives. Economic welfare (contribution to GDP, taxes, etc.) as well as trading opportunities (contribution to foreign currency savings, etc.) are addressed separately.
Socio-Environmental Performance	This criterion considers the contributions of an operational initiative to the improvement of the environment for society on a community, regional and national level. The extension of the environmental monitoring abilities of society, as well as the enhancement of legislation and the enforcement thereof, are included in this criterion.
Stakeholder Participation	**Stakeholder Participation focuses on the relationships between the company and ALL its stakeholders (internally and externally) by assessing the standard of information sharing and the degree of stakeholder influence on decision-making.**
Information Provisioning	The quantity and quality of information shared with stakeholders are measured. Information can either be shared openly with all stakeholders (Collective Audience) or shared with targeted, specific groups of stakeholders (Selected Audience).
Stakeholder Influence	The degree to which the company actually listens to the stakeholders' opinion should also be evaluated. Two separate sub-criteria are included: Decision Influence Potential and Stakeholder Empowerment.

Table 9. Definitions of social Criteria [Labuschagn and Brent, 2006]

3.9 RECOMMENDATIONS AND RECAP

Building technologies provide both positive and negative impacts [Kim and de Dear, 2012]. As a result, the technology implementation should be based on a detailed understanding and appropriate assessment of the context of the project from an environmental, social, economic and technical perspective. Technology performance in a region, programme or building type may differ from performance in another context [Nelms, Russell, and Lence, 2005]. The technologies implemented by society express their culture and how they perceive and involve themselves with systems of nature. These differences by country of origin can be seen as building shapes, to their mode of operation, to the sex of the respondents, and their interpretation of the scale [Humphreys, Nicol, and McCartney, 2002].

An integrative and participatory process is one that considers the relationships between inhabitants and between inhabitants and building systems as interactive and multidirectional, rather than linear or predictable, as is assumed in the conventional approach. There is increasing recognition of the need to move beyond physiological comfort and more considered acknowledgment of users and their engagement with controls and other building environmental features that is sufficient to recontextualize the notion of comfort. The building should be adapted and flexible to the climatic condition and the needs of the users. Climate is a defining variable that influences culture, design of buildings, and people's behaviour. The adaptive model is based on three inter-related aspects: psychological (comfort expectation and habituation to climate), behavioural (opening windows, use of blinds, fans, and doors) and physiological (acclimatization) [Rupp, Vásquez, and Lamberts, 2015]. It has, in addition, been noted that women and men will rate environmental conditions with different scores [Frontczak and Wargocki, 2011; Rupp, Vásquez, and Lamberts 2015; Karjalainen 2007]. Thermal comfort is placed in the context of three essential variables: i) The climate; ii) The building with its services; and, iii) The time users respond to changing conditions. If a change occurs such as to produce discomfort, people react in ways that tend to restore their comfort [Nicol and Humphreys, 1973]. Consequently, a building designed with excellent 'green' performance standards can be severely compromised because specifications and technical performance cannot adequately account for the needs, expectations, and behaviour of the occupants.

Four design strategies can be followed to reach this adaptable concept. First, "Make invisible", those things which are supposed to work only in the background with little or no human intervention. Second, "Make usable", things needing regular attention and/or interaction. Importantly, this is linked to management culture and occupant convenience. Third, "Make habitual", formal and informal rules, which will contribute to safe and comfortable smooth running of the building, although that is more a matter for individuals. Finally, "Make acceptable", things which are not prescribed and covered by the rules, but which allow scope for individuality, innovation and change.

Today, it is necessary to acknowledge additional factors when defining comfort: climate change, and agency and complexity, which provide a new perception for the challenges ahead. The building sector has been identified as a key potential contributor to efforts to mitigate climate change [Metz et al., 2007; Urge-Vorsatz et al., 2007a, 2007b]. It has significant implications for conventional approaches to comfort. Depending on the strategies that are used, it provides additional incentives to redefine and broaden the scope of what inhabitants consider 'comfortable' indoor environments. An integrative and participatory process is one that considers the relationships between inhabitants, and between inhabitants and building systems as interactive, rather than linear or predictable, as is assumed in the conventional approach.

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4 MONITORING AND POST-OCCUPANCY EVALUATION OF A REGENERATIVE INDOOR ENVIRONMENT

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CONTENT

4.1 HOW, WHY AND WHEN TO MEASURE BUILDING PERFORMANCE

4.1.1 WHAT IS POST-OCCUPANCY EVALUATION (POE)?

Post-Occupancy Evaluation (POE), among many other definitions in the scientific literature, has been characterized as "*… the process of evaluating buildings in a systematic and rigorous manner after they have been built and occupied for some time.*" [Preiser, 1995].
Data collection, evaluation and feedback are the cornerstones of continuous improvement in the supply of buildings. A robust data-collection procedure is an intrinsic part of good building briefing and design. POE is a way to obtain this information during the life cycle of a building and is often used as a generic term that can include both: a review of the process delivery of a project; and, an evaluation of the technical and functional performance of the building during the time of its occupancy. Other than driving the operation of the building and its related systems, the information from data collection, evaluation and feedback can also be transferred to future projects.
POE can serve several purposes, including the following:

Short-term benefits

- Identification of building-related problems and definition of possible solutions;
- Response to user needs;
- Improvement of space utilization, based on feedback from users;
- Understanding the implications of changes within buildings (e.g., budget cuts, working context);
- Informed decision-making.

Medium-term benefits

- Built-in capacity for the adaptation of buildings to organizational change and growth;
- Finding new uses for buildings;
- Designer accountability for building performance.

Long-term benefits

- Long-term improvements in building performance;
- Improvement in design process quality;
- Strategic review.

4.1.2 THE IMPORTANCE OF POE

The focus of a Post-Occupancy Evaluation (POE) can be considered in terms of three major areas: a) Process evaluation; b) Functional performance evaluation; and, c) Technical performance review.

a) Process evaluation

The aspects that should be considered are:

Brief	The way in which the team develops the design brief including financial management aspects.
Procurement	The way in which team selection, and contractual and technical processes, among others, are undertaken, including time and value aspects.

Design	The way in which the team develops and refines the design including space planning, engineering and financial management aspects.
Construction	The way in which the construction phase until handover is managed, including financial and change management processes.
Commissioning process	The way in which the final commissioning of the building is managed, including final adjustments and the provision of documentation.
Occupation	The way in which the handover process is managed, including the rectification of last-minute problems and the removal/relocation process.

b) Functional performance evaluation

This evaluation addresses the goals and aspirations of the developer/building owner and how well the user needs are supported:

Strategic Value	Achievement of original business objectives.
Aesthetics and Image	Communication of company ethos, relationship with the context.
Space	Size, relationships, adaptability.
Indoor Environmental Quality	Lighting, temperature, humidity, ventilation, soundscape, control (overall and individual), among other aspects.
Amenity	Services and equipment: completeness, capacity, positioning.
Serviceability	Cleaning, routine maintenance, security, essential changes.
Operational and Life Cycle Cost	Construction investment, energy use, water and waste, leases, cleaning, insurance policies, maintenance and repairs, alterations and demolition.
Operational Management	Space allocation systems, user support systems, help desks, manuals, training, etc.

c) Technical performance review

This review includes measuring the way in which technical systems perform, for example, by including the performance of mechanical (heating, cooling, ventilation) and lighting systems.

Physical systems	Lighting, heating, ventilation, acoustics, etc.
Environmental system	Energy consumption, water consumption, CO2 emissions.
Resilience	Ability to accommodate change and maintain performance levels facing context dynamics.
Durability	Robustness, need for routine extensive maintenance, incidence of “down time” for unplanned technical reasons.

Occupant behaviour has an important role in driving the performance of buildings [Preiser et al., 2014]. If occupants are dissatisfied with their indoor environment, they are likely to take action to meet their comfort expectations [Bolchini et al., 2017]. Occupant behaviour has been identified as one of the most common factors that can help to explain the gap between actual and predicted energy use [Balvedi, Ghisi and Lamberts, 2018]. In this context, POEs focus on analyzing the perceptions and satisfaction of occupants within their built environment, as well as the impact of users on the performance of the buildings [Agha-Hossein et al., 2013]. In POE studies, occupant data can be analyzed in relation to measured indoor environmental parameters (e.g., air temperature, mean radiant temperature, relative humidity, ambient illuminance and noise levels, etc.), thereby linking occupant satisfaction and actions to the conditions recorded in the buildings.

4.1.3 AIMS AND METHODOLOGY

This chapter aims to present a critical systematization of the following:

a) Procedures for conducting Post-Occupancy Evaluation (POE) campaigns (e.g., longitudinal, point-in-time, transversal);
b) Protocols and tools (including the identification of sensors, instruments, etc.) to measure building performance data (related to the Key Performance Indicators (KPIs) presented in Chapter 2);
c) Protocols and tools (including questionnaires, forms, etc.) for collecting quantitative (e.g., surveys, etc.) and qualitative occupant data (e.g., focus groups, structured interviews, etc.).

Considering that several procedures, protocols and tools are currently available, the systematization has been structured through the following methodological steps: 1) review of scientific papers from peer-reviewed journals, online documentation, extracts from books and conference proceedings, among others; 2) collection of information from existing POE providers (e.g., websites, direct contact, etc.); and, 3) analysis of criteria and requirements embedded in current standards and green building certification systems.
For each of the above aspects, the information is presented discussed, and synthetized in tables. A comprehensive reference list at the end of this chapter offers a wide overview of the various literature sources from which all the information presented in this booklet has been gathered.

4.2 POE PROCEDURES

Decisions on POE and monitoring methods are based on contextual parameters such as:
- Location of the building subject to the campaign;
- Type of building (e.g., office, school, hospital, residential, etc.);
- The nature of the problem to address (e.g., humidity, temperature, ventilation, etc.).

These parameters define the choice of one of the three procedures:
- Transversal
- Point in Time
- Longitudinal

The context also affects the selection of monitoring tools depending on the current state of the building and its occupants, and on the available resources [Olivia and Christopher, 2015].

4.2.1 TRANSVERSAL STUDIES

This procedure is used, for example, when the client requires simple and quick analyses of occupant satisfaction levels with a number of indoor environmental qualities or building features and characteristics. The “Transversal” methodology is mainly based on questionnaires and surveys [Frontczak et al., 2012a]. Among these, for example, are the CBE Occupant Survey, the BUS methodology, the SPEQ and Comfortmeter, etc., which are also compatible, and in some case pre-approved, with most existing green building

certification protocols [Wargocki et al., 2012000 occupants collected mainly in US office buildings using a web-based survey administered by the Center for the Built Environment (CBE].
The survey, which is generally administered online to occupants, is delivered in an email that informs the occupants of the questionnaire that is to be completed within a certain period of time. If the occupant forgets to fill it out, a customizable number of notification alerts can then be sent. Upon acceptance, the link to access the online questionnaire is forwarded to the user. The average duration of the questionnaire is 10-15 minutes with an average of 20-30 questions. The answers can be based on a score or on discrete assessment scales (for example, a Likert-type scale with 5-7 points) and with various open-ended questions. These options can reveal further problems for investigation that might have not been reported by the client [Kim et al., 2013; Liang et al., 2014].
The answers to the questionnaires can be stored on an online cloud or on a mass memory database incorporating personal data and privacy protection. The questionnaires are generally based on the expression of satisfaction with a number of categories and parameters, which might include, for example: office layout, furnishings, thermal comfort, visual comfort, temperature, relative humidity, air quality, lighting quality, acoustic quality, cleanliness and maintenance of the building, perceived job performance, etc. [Zagreus et al., 2004]. Once gathered, the data are processed, statistically analyzed and compared with similar cases that have previously been surveyed. The questionnaire can be modified and adapted, in accordance with the building typology or the specific purpose of the analysis [Stevenson, 2009] [Li, Froese and Brager, 2018].
Transversal surveys can be useful for benchmarking purposes, although their standardized questions may not provide a sufficiently detailed snapshot of the complexities of inhabiting buildings, interactions between occupants, both cultural and social behavioural differences and actions, etc. Self-reported satisfaction and comfort responses based on memory may, in fact, provide a limited view from which the full picture may not be established (e.g., tolerances, acceptability, and variations in temporal and seasonal expectations within the buildings, etc.). These limitations may overly simplify the complexity, the diversity and the dynamic use of buildings and the perceptions among occupants of inter-seasonal changes between different building areas or spaces, and between different user types, especially in relation to cultural expectations, within the indoor environment.

4.2.2 POINT-IN-TIME STUDIES

Point-in-time (also known as “right now”) procedures are mostly used when sources of discomfort from IEQ parameters need to be identified and measured. These studies can be conducted in many building typologies, including offices, schools, residences, etc. [de Dear et al., 2018]. The main feature of this methodology is the administration of paper questionnaires (for example, the Snap-Shot BOSSA survey) presenting binary (e.g., YES/NO) answers and Likert scales with relatively short compilation times. Once collected, the data are then sorted under pre-set variables (e.g., age, gender, position, work activity) and catalogued, while preserving sensitive data. While collecting “right-now” information on the perceptions provided by occupants, measurements through sensors positioned on mobile carts, or through specific on-site or hand-held instruments, are taken. Environmental data may therefore be collected at several points, at different times, reducing the installation costs of fixed sensors positioned in each area. The new generation of mobile carts (for example, BOSSA NOVA system) can manage the use of multiple sensors simultaneously, with a quick average data reading. The data can be processed by interactive systems and saved on MicroSD cards or transmitted via wireless connection to a remote server. Some disadvantages of this procedure might be found in the accuracy of the sensors and in the quantity and granularity of the data to be processed; it is important to know the technical specifications of the sensors that are in use, so that the data error range (after calibration) is known. Furthermore, consistent comparisons of different zones of a building cannot be completed without sensors, and manual monitoring campaigns are often only limited to a few hours a day [Stevenson, 2019], [Wong, Mui and Hui, 2008], [Kim et al., 2016], [Wagner et al., 2007], [Hirning et al., 2013].

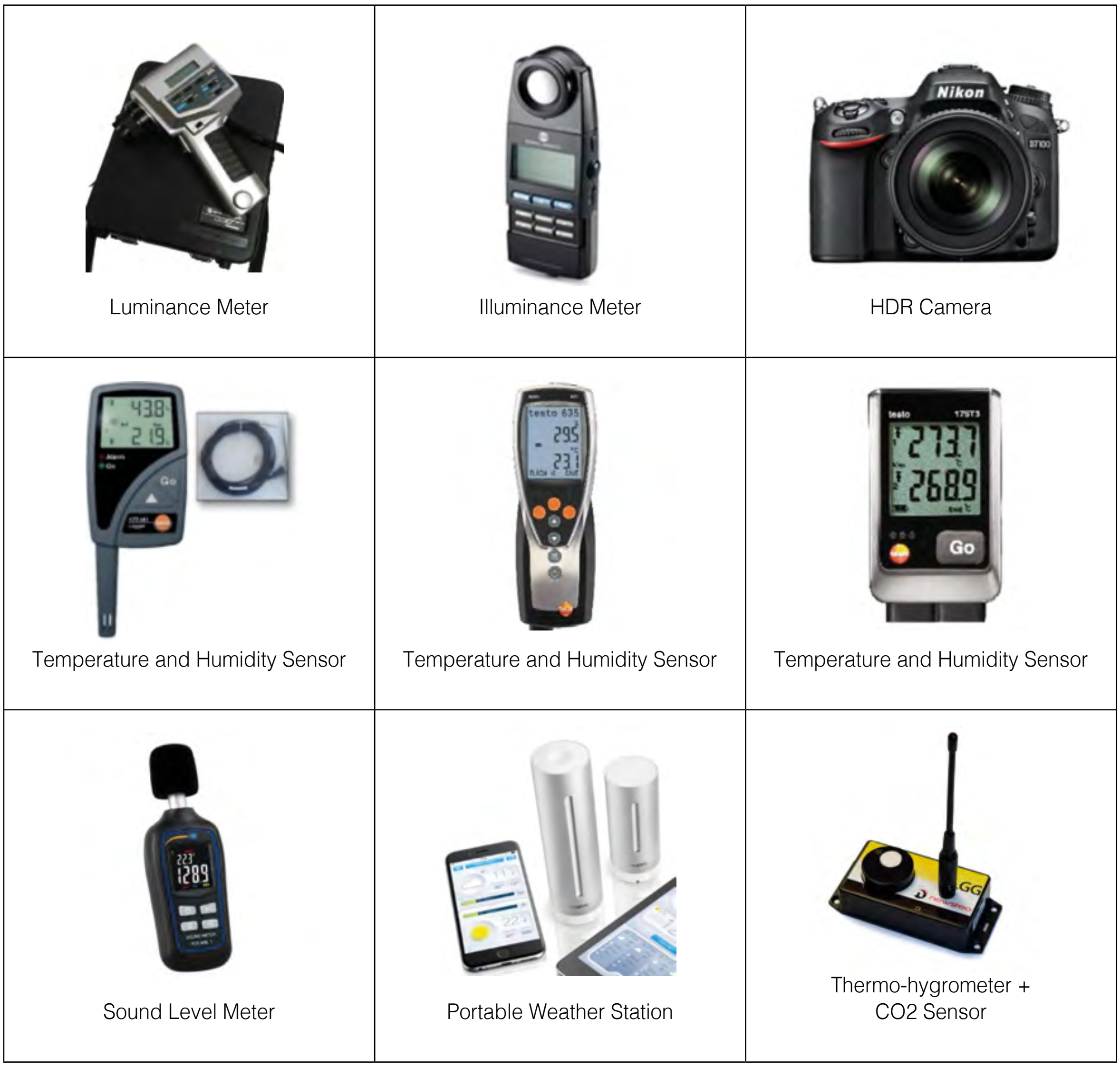


Figure 16. Examples of hand-held instruments for point-in-time studies

4.2.3 LONGITUDINAL STUDIES

Longitudinal studies are used to analyze the perception of environmental comfort, and the continuing evolution of indoor environmental parameters, over a certain period of time. This methodology can be applied to the analysis of different building typologies (e.g., schools, universities, office buildings, etc.). Questions to occupants might be presented as pop-ups on computer screens or via mobile apps, requiring simple feedback on specific aspects to be given with a response score based on a Likert scale or a binary (e.g., YES/NO, hot/cold, positive/negative, etc.) response. Responses are collected and organized in accordance with pre-set parameters [Berquist et al., 2019]. These monitoring campaigns can be supported by physical measurements and/or by energy simulations of the building to which the POE analysis is applied [Konis, 2013; Jin et al., 2018; Karami et al., 2018; Kim et al., 2019]

The weakness of this procedure is mainly related to the composition of the questionnaire; the few questions based on simplified (e.g., binary code) answers might be insufficient for the collection of extensive feedback that could be used for further exploration of the causes of occupant-perceived environmental discomfort. Moreover, with this evaluation procedure, the correlation of responses with IEQ parameter readings would require the installation of fixed sensors (or, for example, wearables) that can continuously record the evolution of the environmental conditions, so that the information may be correlated with the times when feedback is provided [Gucyeter, 2018; Piselli and Pisello, 2019; Pritoni et al., 2017; Gonzalez-Caceres, Bobadilla and Karlshøj, 2019; Parkinson et al., 2019a; Parkinson et al., 2019b].

4.3 SURVEY QUESTIONNAIRES

4.3.1 THE ROLE OF OCCUPANTS WITHIN THE INDOOR BUILT ENVIRONMENT

On the one hand, indoor environmental quality can have significant effects on any user of a building. On the other hand, occupants can strongly influence the performance of a building thorough their actions and behaviours. Consideration of such issues can lead to better control strategies, to a better estimation of the final energy demand of a building and, finally, to better indoor conditions [Choi et al., 2012]. Considering the performance of a building as a whole, two different perspectives should be taken into account: (i) building performance in terms of construction, technical, technological, physical and climate-related factors; and, (ii) building performance in terms of the so-called human factors, i.e. occupant behaviour, indoor environmental quality, control actions, social dynamics and attitudes.

Despite the UN Office of the High Commissioner for Human Rights promoting recommendations on the enjoyment of safe, clean, sustainable and healthy environments [UN General Assembly, 2012], occupant behaviour and wellbeing in indoor spaces are still treated in a marginal way. In fact, only a few references can be extrapolated from the most recent legislative documents. Directive 2012/27/EU [EU, 2012] establishes that Member States must promote measures for behavioural change among the occupants of existing buildings and to increase public awareness of energy efficiency. Directive 2018/844/EU [EU, 2018] focuses on the use of smart readiness indicators, in order to adapt the operational strategies of the building to the needs and attitudes of occupants, as well as to increase user confidence in energy saving strategies. From a perspective of indoor environmental quality, the Directive states that better performing buildings must also improve occupant comfort and health conditions. In this direction, Member States have to promote the requalification of existing assets, so as to enhance indoor conditions for users.

In this context, building occupants can play a double role:

- As *active* users, they can interact with the environment and modify it, so as to meet their needs for comfort and wellbeing. The consequence of such operational actions is a modification of the state of a building, which leads to changes in its performance and energy requirements.
- As *passive* users, dwelling in a particular indoor environment, they are subject to its conditions, which can have certain repercussions, on both their comfort and wellbeing and, in consequence, on their performance, mental state and health.

The achievement of energy and IEQ goals depends both on the technical features of a building and on the key-role of its occupants. In fact, the difficulty of bridging the gap between actual and predicted energy needs has, at least partially, been attributed to the as yet incomplete characterization of occupant behaviours in response to environmental stimuli [Delzendeh et al., 2017]. While the need for adequate indoor environmental quality is regulated by standards and codes, and has largely been investigated in research, the behaviour of occupants and their interactions with environmental controls still represent a 'grey' area that has only recently received attention. Occupants are still often modelled in simplistic ways, as passive subjects rather than active and adaptive agents. However, consideration of both the role of the occupant within the environment and IEQ aspects, can lead to a better understanding of building performance and to the identification of the most suitable and effective management strategies, in relation to different dynamics between users and their environment.

4.3.2 ASSESSMENT OF IEQ CONDITIONS

Ensuring good IEQ conditions is a fundamental requirement, because it directly affects health aspects, occupant productivity, cognitive activities, mood and motivation. According to [Mishra and Ramgopal, 2015], several studies have confirmed the crucial role of indoor environmental conditions on occupant performance, although there is scarce little research encompassing all aspects of IEQ. Instead, most studies have been centred on thermal and ventilation aspects. These two areas, besides having important effects on health and productivity, are in fact strictly related to energy use.
In the literature, different methods have been used to evaluate environmental conditions within indoor spaces. In terms of the comprehensiveness of the studies, two approaches can be recognized:
- *single aspect:* focus on just one IEQ area at a time;
- *comprehensive approach:* simultaneous assessment of all IEQ areas.

As pointed out in the previous section, surveys and data collection can be based on different approaches and assessment methods:
- *subjective:* administration of response survey questionnaires to occupants;
- *objective:* short/long term monitoring campaigns of indoor environmental parameters;
- *numerical analysis:* based on calculations or application of existing models and standards;
- *model simulation:* use of dynamic simulation to assess building performance.

Despite the difficulties, a complete assessment of indoor environmental conditions is better achieved through a comprehensive approach, which implies the simultaneous evaluation of the thermal, olfactory, visual and acoustic qualities perceived by occupants. In fact, any discomfort in each one of these areas could compromise the experience of users within the indoor environment. As mentioned, different assessment methods can be used to evaluate conditions in buildings, together with analyzing human behaviours within indoor spaces. However, consistent and robust methodologies are nowadays often hard to find. The current challenge is to outline and to elaborate a standardized method, in order to implement IEQ evaluations, using an efficient and structured approach. In fact, although standards offer recommendations on ways of gathering user feedback in practice and performing energy audits, systematic methods to implement subjective assessments through methodical, repeatable and uniform approaches are still missing, especially when related to personal perceptions. The consequence is that subjective evaluations are often performed, based on the researchers' best knowledge, thus obtaining data that are difficult to integrate together in a comprehensive database. As mentioned, besides transversal (also known as cross-sectional) appraisals of occupant satisfaction, two further approaches can be found in the literature: long-term longitudinal campaigns and point-in-time/right-now surveys. The former refers to questionnaires that are periodically administered at different times throughout the year and that are repeated in selected spaces of the building, without necessarily taking simultaneous objective measurements. Conversely, right-now surveys are administered at selected times, in specific spaces, while IEQ monitoring is simultaneously taking place. In general, a survey questionnaire can be structured, so that general information, demographics, and anthropometric data may be gathered from the occupants, as well as their perceptions and/or levels of satisfaction with the different IEQ areas, i.e. thermal, visual, acoustic and air quality [Pastore and Andersen, 2019]. For each domain, different questions are presented using various typologies of evaluation scales. Scales can be used in different ways, sometimes modified depending on the purpose of the survey, in order to grasp diverse information by looking at subjective patterns of votes, depending on the objective that is pursued.

4.3.3 EVALUATION SCALES

A brief review of the most common scales is summarized below in Figure 17.

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

(A)

Vote	Sensation
+3	Much too warm
+2	Too warm
+1	Comfortably warm
0	Comfortable
-1	Comfortably cool
-2	Too cool
-3	Much too cool

(B)

Vote	Sensation
7	Very satisfied
6	
5	
4	
3	
2	
1	Not satisfied

(C)

Temperature preference
Hotter
No change
Colder

(D)

Vote	Sensation
+1	Clearly acceptable
0	Just acceptable
0	Just unacceptable
-1	Clear unacceptable

(E)

Figure 17. Examples of evaluation scales referring to the thermal environment

a) Perception scale: used to assess occupant perceptions of the indoor environment. Although it is based on the thermal comfort model proposed by Fanger [Fanger, 1970], this scale is also usually extended to other IEQ areas. It consists of a Likert scale, with votes ranging from -3 to +3 and with a neutral central point, 0. People voting from -1 to +1 are generally assumed to be comfortable. This scale is commonly featured in standards such as EN ISO 10551 [CEN, 2001], EN ISO 7730 [CEN, 2005], and in ANNEX H of EN 16798 [CEN, 2019] and ANSI/ASHRAE Standard 55 [ASHRAE, 2013]. For thermal studies, the scale is also known as Thermal Sensation Vote or ASHRAE Scale.

b) Bedford scale: as an alternative to the above scale, this is a 7-point scale, graded from -3 to +3, where the central point, 0, stands for the comfortable sensation. This evaluation scale is an attempt to combine the comfort acceptability of the environment with information on the perceptions.

c) Satisfaction scale: used to denote satisfaction graded by increments in satisfaction from 1 to 7. This scale is featured in ANSI/ASHRAE Standard 55 [ASHRAE, 2013]. In the literature, similar examples of this scale feature 4, 5 and 13 points. However, in a seminal paper on cognitive information processing, [Miller, 1955] indicated that the human ability to process information and make judgments significantly decreases with more than 7 simultaneous alternatives, thereby suggesting that multi-choice scales should be limited to between 5 and 7 options.

d) Preference scale: also known as the McIntyre scale, this scale is used to gather information on user preferences towards their actual environmental conditions. It is a scale with 3 options, proposed in the ANNEX H of UNI EN 15251 [CEN, 2007].

e) Acceptability scale: a 4-point scale, which gathers opinions on levels of acceptability of the environment, although it provides no information on perception. Introduced in 1992, it is reported in ANNEX H of UNI EN 15251 [CEN, 2007].

Evaluation scales can be presented in various graphical ways, with different levels of detail. No standard gives specifications on the choice of the most suitable configuration; thus, the selection is often a matter of the specificities of the study. The main difference between the various types of presentation is given by the level of accuracy and the visual hints presented to the survey participant. Scales can be partially or completely labelled, depending on the required level of accuracy. Scales can also be presented with a vertical or horizontal arrangement. In the case of questionnaires administered to children, it can be useful to simplify the ability of processing information and giving responses using graphical tools and drawings. In this case, Visual Analogue Scales [VAS], composed of single lines with anchor descriptors at each end, are recommended.

4.3.4 SURVEY ELABORATION PROCESS

As stated before, no standardized survey methodology is specified in building codes. Developing a survey is therefore a stepwise approach, which can be summarized in the following phases.

Phase 1. In this phase, it is important to define the design of the experiment or data-collection campaign. Hence, the objectives must be identified, along with the definitions of the analyses and the evaluations that will be performed with the survey data. The aim of this phase is to set out, in advance, the goals that are to be achieved and the necessary analysis, so as to draft the survey questionnaire in the most suitable way. For example, this can include:

- main objective;
- selected investigation areas;
- types of questions and evaluation scales;
- additional evaluations;
- restricted focus;
- methods for statistical analysis.

Phase 2. In this phase, the questionnaire will be elaborated. It is important to approach this task with knowledge of the selected occupants, in particular their cognitive levels and information processing capabilities, especially when it involves young occupants. For example, if the sample of analysis includes infants, there can be no interactions with them, due to their inability to understand the questions; thus, the assessment of comfort sensations can be derived from physiological factors or from indirect experiments conducted by specialists. Apart from individual cultural issues and social processes, adolescence is, unlike infancy, a growth period where the capability to understand questions is comparable to the understanding of adults.
Aside from evolutionary phases, environmental and social aspects strongly influence human perception and responses. According to the user-centred theories for the built environment, two different positions can be identified: (i) environmental *determinism*, in which the environment is assumed to be a determiner of user behaviour; (ii) social *constructivism*, in which the human attitudes are determined by the social context. Although the first position is favoured for its immediate applicability, it can minimize and oversimplify all the possible variables that drive human behaviour, whereas human experience is also highly influenced also by social norms, interactions and constructions. According to [Vischer, 2008], a user-centred theory is located between these two extremes: subjective behaviour is influenced, but not determined by the environment, while it is affected by such other aspects as feelings, intentions, attitudes, expectations and social context.

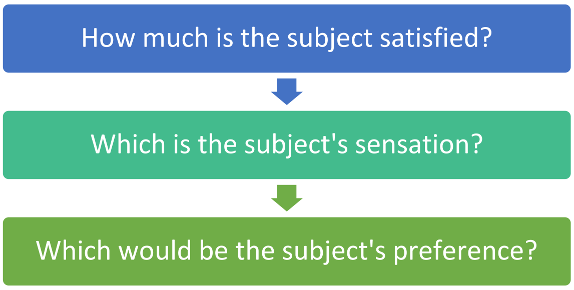
This perspective is quite remarkable, if we think about shared indoor environments, where social context and occupant-to-occupant relationships could play an important role in determining the individual actions and feelings within the group environment. According to [Watson et al., 2016], group mechanisms include: (i) organizational cultures, referring to both organizational and institutional social order; (ii) management strategies or the processes that control individual users and user groups; and, (iii) social norms and practices, referring to the tacit knowledge and related behavioural patterns of individual users. In these challenging scenarios, a multi-level comprehensive approach could be useful, so that the different factors may be grasped that influence personal experiences where the human-environment chain of cause and effect is more complex and less linear, and takes into consideration environmental, individual, and group stimuli [Barrett et al., 2013]. Data collection on occupant experiences within indoor environments should therefore gather sufficient information to grasp aspects that are related to individual attitudes and group dynamics, as well as to satisfaction and individual perceptions. Understanding the process that leads to action or non-action towards environmental conditions could be a significant step forward in the elaboration of user-oriented management strategies. From this perspective, a multi-disciplinary approach towards the elaboration of POE surveys is certainly needed.

Structuring the survey questionnaires

The structuring of a survey questionnaire is proposed in the following sections.
Section 1 - Instructions. Occupants are provided with some information before filling in the questionnaires. A brief explanation of the reasons for the survey are given, so that users will feel part of the project as active occupants of their own building. Making the users aware of the general scope of the research can raise their awareness and motivate them to disclose personal data. Finally, indications on the evaluation scales and the different types of questions are provided.
Section 2 - Demographics and anthropometrics. Occupants respond to requests for personal information of a general nature. For example: (i) gender; (ii) year of birth; (ii) weight; (iv) height; (v) work-type; and, (vi) date and time. The aim is to collect the main physical and psychological characteristics of each user, for eventual correlation with the responses. For example, some generalization could be found regarding comfort preferences depending on the gender, body mass, etc. In addition, users might be asked other questions related, for example, to the clothes they are wearing, e.g., estimate their clothing thermal insulation, if they are facing any psychological stress, e.g., to assess their general mood, etc.
Section 3 - General comments and specific questions. The aim of inviting occupants to express their general comments is for a better characterization of their satisfaction levels with the building and to identify potential aspects that might affect their answers. Different aspects can in fact influence subjective responses: for example, the satisfaction level might be affected by the level of appreciation of the general social context and of the interpersonal relationships. In addition to this, specific questions may be posed that, for example, inquire into levels of interest in the energy consumption of a building. These questions could then be evaluated on a Likert satisfaction scale or via binary (e.g., yes/no) answers. Some questions on occupant behaviour towards energy efficiency might also be asked: an individual occupant might be required to indicate their level of action towards simple energy conservation measures, and the reasons leading to an active/passive behaviour. Finally, the specific location of the occupant during the survey is considered, so that the responses may, wherever possible, be linked with the configuration of the room/built environment (or with simultaneous environmental monitoring).
Sections 4 to 7. The views of occupants and their feedback on indoor environmental qualities are shown here. These sections will all generally follow the same structure, which can be summarized as follows.

1. Perceived control over the environment: users are asked to indicate the types of control available for modifying their surrounding environment. This information is useful to understand if there is any gap between the real control provided by building systems and the control levels perceived by the occupants.
2. Level of satisfaction with each specific IEQ domain: evaluated for each domain, it can be ranked by the subject with a Likert-type scale of either 5 or 7 points.

3. Comfort sensation: rated, for example, on a scale from -3 to +3, the responses provide information on user perceptions, in relation to a specific IEQ domain.
4. Preference: using, for example, the McIntyre 3-point scale, the subject can express a preference regarding their actual environment. This question follows those on satisfaction and sensation, in order to follow, as with the survey elaboration process, the following logical sequence:



1. Attitude: in this part, the aim is to grasp user attitudes and behaviour towards a sensation of discomfort. The goal is to understand whether subjects take action by themselves or whether their behaviour is reliant on a leader or other users, and therefore influenced by the social context and group dynamics.

Optional modules:
2. Room/space setup: users can give some information on the configuration of the room or space they are occupying and provide additional details on the system operation. This approach is especially useful in the case of long-term surveys, when the researcher might not be able to carry out a direct appraisal of the conditions under which the responses would be provided.
3. Reasons and patterns of discomfort: the underlying purpose of this question is to identify the reasons for discomfort in each IEQ domain, according to occupant opinions, and to recognize potential patterns of discomfort. A picture that will give a better grasp of possible problems and malfunctioning as perceived by the occupants, with a view to the preparation of better control and management strategies, thereby ensuring acceptable IEQ conditions, whilst fostering energy-saving strategies.

Phase 3. This phase defines the way that a survey questionnaire is best administered to occupants, in particular concerning the choice of surveyed locations, representative times, and the delivery method. Online-based surveys and mobile applications could be used, because they can encourage user engagement, facilitate data collection and processing, and gather information from occupants with a tool that is nowadays part of their everyday routine. According to UNI EN 15251 [CEN, 2007], surveys should be administered in representative spaces within the building, at representative times throughout the year.

Phase 4. In this phase, results are elaborated and analyzed, matching the goals set in Phase 1. For each IEQ domain, the main questions are framed that are considered significant for the proposed objectives. The flow chart shown below in Figure 18 is proposed.

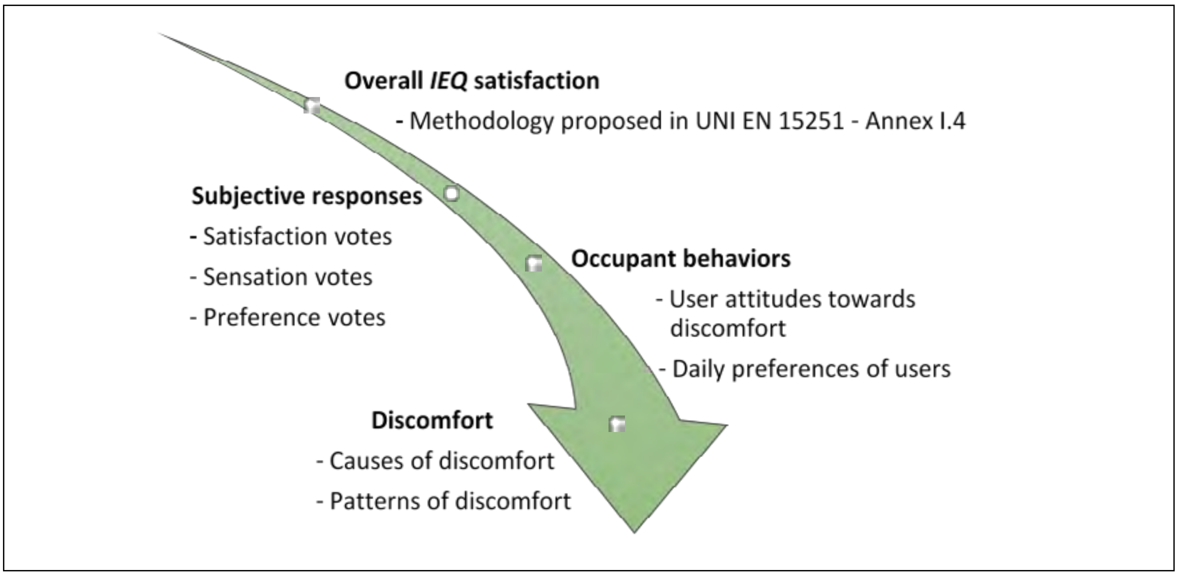


Figure 18. Data-elaboration process

1. *Overall IEQ satisfaction evaluation methodology, proposed in EN 15251 [replaced, in 2019, by EN 16798-1].*
   The method prescribed in EN 15251 – Annex I.4 [CEN, 2007] can be applied to evaluate the overall IEQ inside a building. According to the aforementioned standard, "*the percentage of people voting acceptable (thermal environment and air quality) is calculated for each of the representative spaces in the buildings. A weighted average according to the number of people in the different spaces is calculated and used for classification. More details can also be included by showing the distribution of votes on the 7-point thermal sensation scale and showing the percentage of people wanting higher, no change and lower room temperatures*". Even though this approach is only proposed for thermal comfort and air quality, it can be adapted to the other domains of indoor environmental quality.

2. *Satisfaction votes, perceived subjective sensation and occupant preferences.*
   As suggested in the standard, more details are added to the analysis where relevant. Answers on a Likert 7-point scale are taken into consideration for the assessment of satisfaction (votes higher than or equal to 4 can be considered as an expression of user satisfaction). In addition, more detailed information can be reported, such as the percentage of answers under both the sensation vote scales (-3/+3 perception scale) and the preference vote scales (3-point McIntyre scale).

3. *Occupant behaviour*
   Some further details on occupant behaviour and attitudes towards discomfort can be presented, together with the user preferences in the survey on their indoor environment in everyday life.

4. *Discomfort causes and patterns*
   Finally, analysis can be performed, for insight into the main causes of discomfort and the patterns of their occurrence.
   Focusing on subjective evaluations, the proposed stepwise methodology enables the final administration of a tailored questionnaire, considering both the building typology and the occupants. This approach allows us to:
   - gather occupant responses regarding the main IEQ domains;
   - understand user satisfaction levels and comfort perceptions;
   - assess user preferences within the indoor environment as well as in everyday life scenarios;
   - understand occupant behaviour, attitudes and actions in reaction to discomfort;
   - gain a deeper understanding of user moods and psychological attitudes;

- grasp potential group dynamics and social norms that can affect the individual will of the occupants;
- evaluate potential recurrent patterns in perceived discomfort.

Further developments of the methodologies for delivering and collecting data from survey questionnaires still need to be carried out, especially in the field of user behaviour. To do so, an inter-disciplinary approach is required, so as to identify physical, physiological and psychological factors, particularly in shared spaces (e.g., group dynamics), that can strongly affect the individual occupants.

4.4 POE PROTOCOLS

Figure 19 below provides an illustration of the structure of POE protocols, looking specifically at measuring the operational performance of buildings (e.g., energy, water use, wastes, etc.), parameters of indoor environmental quality (e.g., air quality, lighting, thermal comfort, soundscape, etc.), and the satisfaction levels of occupants towards building features and/or interior spaces.

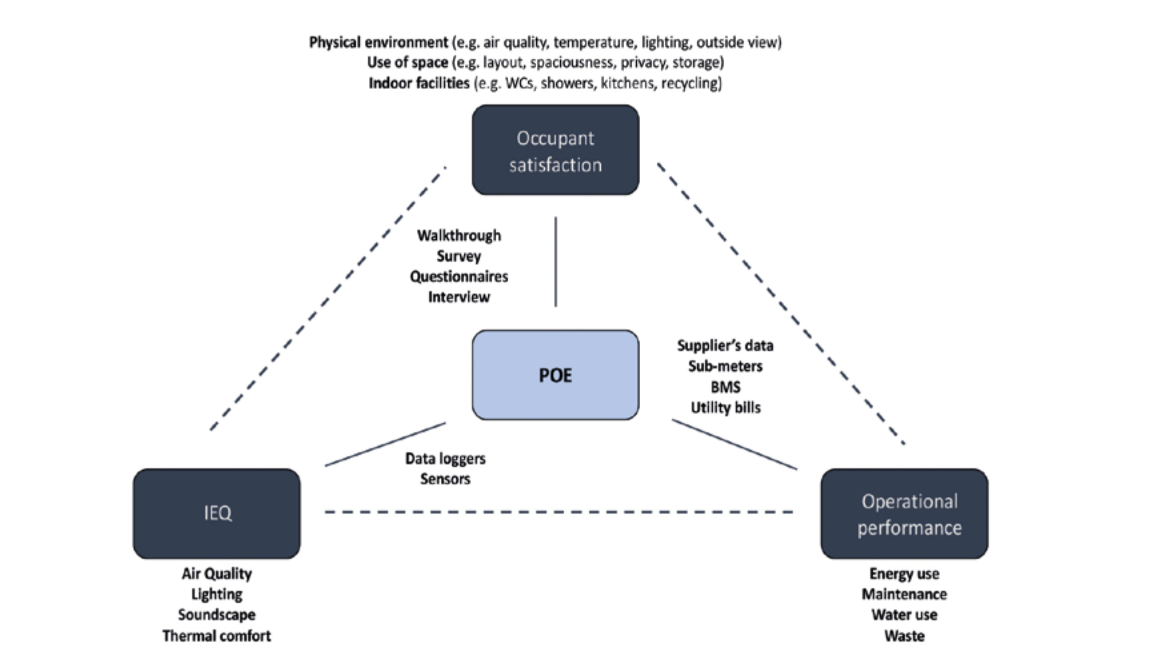


Figure 19. Structure of POE Protocols

Table 10 lists the main POE protocols that are available for the performance of post-occupancy evaluation and monitoring campaigns. These protocols have been selected, based on the vast scientific literature available on their application and the fact that they are considered as "pre-approved" third-party survey providers under the criteria established by several building codes and certification tools, such as the International WELL building standard v.2 [WELL, 2019a].
The table below illustrates the type of POE procedure (e.g., transversal, point in time, longitudinal), the assessment method, the type of evaluations that are performed, the categories that are analyzed, compatibility issues with green building certification systems and other standards, the common types of buildings under analysis, and the availability of online links and references.

Table 10. POE Protocols

Protocols	Procedure	Method	Evaluations	Notes	Categories	Standards	Type Of Building	References
CBE Occupant Survey	Transversal	Online Questionnaire	Collection of questionnaires to monitor performance and plan strategies	Survey valid if users occupied the building for last 6 months	General building, Workspace, Cleanliness, Ease of Interactions, Amount of light, Comfort of furnishing, Amount of Space, Visual Comfort, Colours and Textures, Furniture Adjustability, Visual Privacy, Noise level, Temperature, Sound Privacy	LEED and WELL	Office, Laboratory, School, Residence, Health Care, etc.	Zagreus et al., 2004
BOSSA TIME-LAPSE	Point in time	Right now Questionnaire	Occupant questionnaire on key aspects of their indoor space	Pre- and Post-evaluation criteria	Indoor Air Quality, Spatial comfort, Noise distraction, Sound privacy, Connection to Outdoor, Building Image and Maintenance, Individual Space, Thermal Comfort, Visual Comfort, Perceived Health and Productivity, etc.	NABERS and LEED	Commercial Buildings	Cândido et al., 2013b
SNAP-SHOT BOSSA	Point in time	Right now Questionnaire	Occupant questionnaire to evaluate the qualities of indoor spaces	Measurement real-time	Thermal Comfort, Visual Comfort, Acoustics, Indoor air quality	WELL	Commercial Buildings	Cândido et al., 2016a
BOSSA NOVA	Point in time	IEQ mobile + Right now survey	Mobile instrument equipped with sensors	Measurement real-time	Thermal Comfort, Visual Comfort, Acoustics, Indoor air quality	WELL	Commercial Buildings	What is BOSSA?
BUS	Transversal	Online questionnaire	Questionnaire focusing on the perceptions and wellbeing of the occupants	Before or after the operation	Work organization, Water, Nutrition, Movement, Mind and Community Programmes, etc.	WELL, BREEAM and LEED	Commercial Building, Residences, Healthcare, Schools, etc.	CIBSE – PROBE Studies
Space Performance Evaluation (SPEQ)	Transversal	Online questionnaire	Online questionnaire with 76 questions and 7 different categories	Survey focusing on quality, comfort performance,and health of the workplace	Thermal Comfort, Visual and Acoustics, Air Quality improvement	LEED and WELL	Commercial Building, Residences, Healthcare, Schools, etc.	Space Performance Evaluation Questionnaire (SPEQ)

Protocols	Procedure	Method	Evaluations	Notes	Categories	Standards	Type Of Building	References
Leesman Index	Longitudinal	Online survey	Survey focusing on the future organization of the company, decisions and investments	Before or after the operation	Collaboration, Environmental Design, Facilities and Services, Furniture and Layout, Indoor Environment Quality, Technology, etc.	WELL	Workplace	What is the Leesman Index and what is it measuring? Leesman, PF 1497 Annex 3 Employee Experience & Workplace Performance | Leesman
Occupant Comfort & Wellness Institute Built Environment	Longitudinal	Online survey	Performance survey focusing on the workplace	Before or After the operation	Office Layout, Workspace, Thermal Comfort, Air Quality, Lighting, Acoustic Quality, Building cleanliness, Wellbeing and Health, etc.	WELL	Workplace	Occupant Comfort & Wellness Surveys
Comfortmeter	Transversal	Online questionnaire	Web-based survey tool that assesses user satisfaction with office buildings	Survey valid if the occupants moved into the building over the past 12 months (1 winter and 1 summer)	Indoor Environmental Quality and Wellbeing	LEED and BREEAM	Office, Schools, University, Retail, Industry, etc.	Comfortmeter Building Performance
BeWell LeadWell *Women *Coaching *Leadership Circles	Transversal	Online questionnaire	Questionnaire of 133 questions divided into 6 categories and 19 sub-categories	Survey to improve leadership in the workplace	Prosperity, Fuel, Flow, Wonder, Wisdom and Amplified Prosperity, etc.	WELL	Work Activities, Offices	BE WELL LEAD WELL®
OHFB Afriforte	Transversal	Online questionnaire	Service for the company to maximize profits	Guide to profit maximization and investment	Productivity, Absenteeism, Customer satisfaction, Incidents Employee turnover, Safety	WELL	Work Activities, Office	Afriforte – Metrics that matter

4.4.1 CBE OCCUPANT INDOOR ENVIRONMENTAL QUALITY (IEQ) SURVEY

The CBE Occupant IEQ Survey is a protocol and webtool based on 20 years of research and developed by the Center for the Built Environment (CBE) at the University of California, Berkeley (USA). It allows building managers and researchers to assess the performance and effectiveness of different built spaces and for easy acquisition of structured feedback from the users. The survey has been implemented in over 1,000 buildings around the world, with responses from over 100,000 occupants. It is completely anonymous and provides comparative statistics on the responses against benchmarks from a vast database featuring information from other buildings, for improvements to management decisions [Frontczak et al., 2012b]. The feedback collected via the occupant survey toolkit can facilitate the identification of problematic areas and the proposal of solutions. This tool helps to meet the requirements of many certification programmes including LEED and WELL. The survey, a component of the Transversal POE procedures, is structured into several categories. For each category, occupants are requested to indicate their level of satisfaction on a Likert scale ranging from -3 to +3. The categories include, among others, the following:

- General Building: expressing overall satisfaction with the building;
- General Workspace: collecting overall perceptions of the workspace;
- Office Furnishings: gathering comments on ergonomics and materials;
- Office Layout: exploring perceptions of storage, space, and privacy;
- Maintenance: understanding the effect of operations, cleaning, etc.;
- Air Quality: identifying sources of pollutants;
- Thermal Comfort: gathering feedback on temperature and air movement;
- Lighting: examining the impact of electric and natural illumination;
- Acoustic Quality: assessing speech privacy and noise levels.

The survey is applicable to many types of buildings including offices, laboratories, schools, residences, healthcare facilities, etc. Over time, new modules have been added to improve the granularity of the questionnaire and obtain more detailed feedback related to specific aspects of investigation. The survey is valid if the building has been occupied for at least 6 months.

Further information available at: https://cbe.berkeley.edu/resources/occupant-survey/

4.4.2 BOSSA

The Building Occupants Survey System Australia (BOSSA) is an IEQ assessment protocol for Australia's office buildings aimed at improving occupant health, comfort and productivity. BOSSA is endorsed for use by the National Australian Built Environment Rating System (NABERS) promoted by the Green Building Council of Australia and the New Zealand Green Building Council [Cândido et al., 2016a].
The BOSSA system includes the following tools:

- BOSSA TIME-LAPSE: This is a transversal survey tool aimed at assessing occupant satisfaction and IEQ performance of office buildings. It can be used to address NABERS, LEED and WELL pre- and post-occupancy evaluation criteria. The core questionnaire items ask building occupants to rate their overall satisfaction on key IEQ dimensions, including among others:
  - Indoor air quality and air movement;
  - Spatial comfort;
  - Noise distraction and privacy;
  - Connection to outdoor environment;
  - Building image and maintenance;
  - Individual space;
  - Thermal comfort;
  - Visual comfort;
  - Perceived health and productivity.

- SNAP-SHOT BOSSA: a point-in-time questionnaire administered to the occupants of a work space to assess the environmental quality within their work area. It is available in four modules: Acoustics, Thermal Comfort, Visual Comfort, and IAQ. The questionnaire is accompanied by simultaneous real-time IEQ measurements.
- BOSSANOVA: an IEQ point-in time-mobile assessment cart equipped with an integrated array of sensors that, combined with the SNAP-SHOT BOSSA questionnaire, allows the collection of high-resolution IEQ data. The instrument includes sensors for thermal comfort, IAQ, lighting and acoustics.

Further information available at: http://www.bossasystem.com/

4.4.3 BUS

The BUS methodology was created about 30 years ago on the basis of 70,000 surveys administered in the context of the PROBE studies [Leamann and Bordass, 1999]. PROBE was a research project (1995-2002) funded by the UK government and implemented by the Builder Group, Energy for Sustainable Development (ESD), William Bordass Associates. The methodology was based on standardized survey methods, based on the collection and evaluation of the energy consumption of buildings and their occupant data.
The Building User Survey (BUS) is a transversal questionnaire investigating the performance of buildings on the basis of responses from their occupants. The BUS questionnaires can be applied to study domestic and non-domestic buildings and transient spaces. BUS facilitates benchmarking and comparisons of measured building performance and occupant satisfaction. Data are collected to identify the views and the satisfaction levels of occupants, from which the capability of the building to meet the physical, psychological and health needs of occupants is inferred. The participants rate their overall perception of comfort in the building in summer and winter, their satisfaction with the design, with aspects of environmental control and with overall performance. The BUS methodology is extremely useful for benchmarking and comparison purposes. The main points consist of the identification of the features to be improved, evaluation before and after the intervention, and compliance with the POE criteria that can contribute to the achievement of certifications including BREEAM, LEED, WELL, and NABERS.
Within the tools and frameworks promoted by BUS, Soft Landings was introduced, in 2008, by the Building Services Research & Information Association (BSRIA) and was extended, in 2010, to the school building sector [BSRIA, 2008]. It was implemented in 2014 with the new RIBA 2013 work plan. Soft Landings is used for new constructions or renovations of existing buildings; it increases the sensitivity of performance in the early stages of briefing and feasibility; it helps set specific objectives by coordinating the roles of designers, builders and operators; and, it helps manage expectations concerning the design, construction and commissioning of the building in the first weeks after the intervention, through monitoring, reviews, and responses from the occupants, to make the best possible use of the work spaces. The monitoring is performed in the first weeks immediately after the operation, after the first year of occupation and then for the second and third year.
In 2009, the BUS methodology was acquired by Arup to create the BUS partner network. Recently, the Arup Building Performance team has partnered with Delos to promote compliance with the WELL v.2 Building standard via the creation of a new survey called the BUS Wellbeing Survey. New question items have been introduced on the quality of the workplace and work organization, water, nutrition, movement, mind, community programmes, etc.

Further information is available at:
https://www.cibse.org/knowledge/building-services-case-studies/probe-post-occupancy-studies
https://www.usablebuildings.co.uk/

4.4.4 SPACE PERFORMANCE EVALUATION QUESTIONNAIRE (SPEQ), HIGH PERFORMANCE ENVIRONMENTS LAB (HIPE)

The Space Performance Evaluation Questionnaire (SPEQ™) from the HiPE Lab (University of Oregon) has been developed and tested in a variety of building types since 1998. It has been applied to evaluate more than 150 buildings to date, with a robust database containing more than 100 LEED™ and other green certified buildings. It provides a wide series of questions to benchmark buildings against comparative baselines. The online survey of occupants features categories and scales identified as affecting occupant comfort, satisfaction, performance, health, and wellbeing. SPEQ™ has been cross-tested and calibrated in the field and in lab settings. The transversal questionnaire evaluates 30 issues in 76 questions classified into 7 main categories. All questions contain a skip-logic approach, to avoid irrelevant information that the respondent might otherwise have to provide, so the questionnaire becomes more effective and less tiresome. The average response time of the questionnaire is 12 minutes.

Further information available at: https://hipe.uoregon.edu/

4.4.5 LEESMAN INDEX

The Leesman index aims at measuring the experience of employees, acquiring feedback on the quality of the workplace, by comparing it with a database that collects the experience of thousands of office workers. The tool awards a Lmi score of between 0 and 100; workplaces with a scores of 70 or higher, with a minimum of 50 respondents and a maximum error margin of 5%, are awarded the Leesman+ Certification. The survey has four standardized sections that provide a comprehensive assessment of how well the workplace is functioning for the organization and its employees:
1. Work Activities: what the activities of the employees are and how well these are supported in the workplace;
2. Workplace Impact: how the workplace supports productivity, pride, sense of community, etc.;
3. Physical and Service Features: which physical features are important to the employees and how satisfied the employees are with those features;
4. Mobility: the extent of employee mobility within and outside the workplace.

The categories available in the questionnaire include:
- Collaboration;
- Environment Design;
- Facilities and Services;
- Furniture and Layout;
- Indoor Environment Quality;
- Technology.

The responses to the questionnaire can be used to assess employee involvement, the effectiveness of decisions and the benefits of new strategies. It can also be the basis for planning future investments. Additional context-specific modules (e.g., environmental wellbeing, flexible working, etc.) are also available and tailored questions can be added to the standardized survey. The questionnaire can be administered before and/or after the operation as a longitudinal instrument.

More information on: https://www.leesmanindex.com/

4.4.6 OCCUPANT COMFORT AND WELLNESS SURVEY FROM THE INSTITUTE FOR THE BUILT ENVIRONMENT AT COLORADO STATE UNIVERSITY

The Institute for the Built Environment (IBE) at Colorado State University has developed a survey that addresses comfort, health, wellbeing and performance of building occupants. The survey is primarily designed for use in offices, although future developments plan the integration of residential and multi-family projects. The survey includes the following aspects:
- Office layout
- Workspace adjustability
- Thermal comfort
- Air quality
- Lighting
- Acoustic quality
- Building cleanliness
- Wellbeing and Health conditions

The survey belongs to the longitudinal procedures and customizable items can be added, including tools for management and analysis of responses (e.g., customization of interviews, social networks and programme management for the realization of an action plan for the building analyzed, etc.).

Further information available at: https://ibe.colostate.edu/occupant-comfort-wellness-surveys-2/

4.4.7 COMFORTMETER

Comfortmeter is based on scientific research from 6 European universities supported by the European Commission through a dedicated H2020 project. This tool measures comfort satisfaction in a scientific way and is compatible with the BREEAM, LEED and WELL certifications. The building must have been occupied for at least 12 months, a period of time that implies occupancy over at least one winter and one summer, hence one heating and one cooling season. This transversal satisfaction survey is composed of 59 questions and it is based, among others, on the following parameters:
- Lighting: including healthy natural light, artificial lighting and views;
- Air Quality: including fresh air flow, replacement of polluted air and reduction of contaminants;
- Office Environment: including type of workplace and personalization;
- Thermal Comfort: including air and radiant temperature, humidity, air speed, and activity level;
- Acoustics: including external and internal noise level, reverberation;
- Individual control: including ability to regulate the temperature, open the windows, management of lighting levels, etc.
-

Further information available at: https://www.comfortmeter.eu/

4.4.8 BE WELL LEAD WELL

Well Lead Pulse is an evaluation tool that facilitates transformations toward a new way of thinking about a team and an organization at work. It is the result of scientific research combined with over 30 years of development by Fortune 500, exploring six dimensions that include prosperity, fuel, flow, wonder, wisdom and amplified prosperity. The questionnaire features 133 questions divided into 6 categories and 19 sub-categories focusing on wellbeing and transformation. There are 4 types of programmes:
- Be Well Lead Well Women: 9-month programme for women leaders to develop their leadership;
- Be Well Lead Well Coaching: learning programme for leaders to update their knowledge;
- Executive Wellbeing Program: a programme to provide a personalized, evidenced-based approach to top leaders for wellbeing and optimal performance;

- Be Well Lead Well Leadership Circles: a 9-month programme to accelerate the effectiveness of leaders and leadership teams.

Further information available at: https://www.bewellleadwell.com/

4.4.9 OHFB-AFRIFORTE

The Organisational Human Factor Benchmark (OHFB) is a scientific-based organizational diagnostics suite developed since 1998 by Afriforte and the WorkWell research unit at the Faculty of Economics and Management Sciences of the North-West University (South Africa). The applications of the benchmark include:
- Bringing the human factor into the workplace: integrating the effectiveness of the workplace and quantifying it in the corporate performance of the organization;
- Managing the result: connecting the results of human factors with impact tests;
- Guiding interventions to maximize returns of investments: focusing on risk factors that affect critical results;
- Increasing productivity, understanding the reasons for absenteeism, helping employees in difficulty, forecasting the turnover of organizations to better manage available resources.

Further information available at: http://www.afriforte.com/home/ohfb/

4.5 POES IN STANDARDS AND RATING TOOLS

Table 11 to Table 16 below list the main criteria featured in selected green buildings certification systems (LEED, BREEAM, GREEN MARK and GREEN STAR) and in building standards (WELL v2, 2019a) related to the implementation of post-occupancy evaluation campaigns or building monitoring and surveys.
These criteria will be presented in greater detail in the following sections.

Table 11. POE Criteria in LEED v.4.0

<table>
<tr><th>TYPE</th><th>BUILDING</th><th>CATEGORY</th><th>CRITERION</th><th>C/P</th><th>DESCRIPTION</th></tr>
<tr><td rowspan="2">O+M</td><td rowspan="2">Existing Buildings
Retail
Schools
Hospitality
Warehouses and Distribution Centres</td><td>Indoor Environmental Quality</td><td>Occupant Comfort Survey</td><td>C</td><td>1 Credit

Administer at least one occupant comfort survey to collect anonymous responses regarding at least the following: acoustics, building cleanliness, indoor air quality, lighting, thermal comfort.
The responses must be collected from a representative sample of building users making up at least 30% of the total occupants.
As a minimum, perform one new survey at least once every 2 years.</td></tr>
<tr><td rowspan="5">Innovation</td><td rowspan="3">Occupant Engagement</td><td rowspan="3">C</td><td rowspan="3">1 Credit

Requirement: Feedback on consumption, implementing communication methods to inform occupants of the energy consumption of the building or workspace. It can be done in real time or on a monthly basis, minimum requirement 1 year of occupation of the same space.
Requirement: Occupant responsibility, implement programmes to involve the occupants through communications to contribute to the achievement of the sustainability objectives for the building.
Requirement: Performance evaluation to trace and to document the results for occupants through meetings, specifying the areas to be improved and the performance that has been achieved.</td></tr>
<tr><td>ID+C</td><td>Commercial Interiors
Retail
Hospitality</td></tr>
<tr><td rowspan="3">BD+C</td><td rowspan="3">New Constructions
Major Renovations
Core and Shell
Data Centres
Hospitality
Retail
Schools
Warehouses and Distribution Centres</td></tr>
<tr><td>Design for Active Occupant</td><td>C</td><td>1 Credit

Improve the health of building users through physical activity.
Requirement: Buildings must have at least a stairway that allows occupants to move between floors.</td></tr>
<tr><td>Occupant Comfort Survey</td><td>C</td><td>1 Credit

Administer at least one occupant comfort survey, to collect anonymous responses on, at least, the following: acoustics, building cleanliness, indoor air quality, lighting, thermal comfort.
The responses must be collected from a representative sample of building users making up at least 30% of the total occupants.
As a minimum, perform one new survey at least once every 2 years.</td></tr>
</table>

C=Credit P= Prerequisite

Table 12. POE Criteria in LEED v.4.1

TYPE	BUILDING	CATEGORY	CRITERION	C/P	DESCRIPTION
O+M	Existing Buildings Retail Schools Hospitality Warehouses and Distribution Centres	Innovation	Occupant Engagement	C	1 Credit
					Intention: improving building performance by promoting energy-efficient behaviour among building occupants. Requirement: inform the occupants of the actual energy consumption of the building, in real time or through a reporting mechanism on a monthly basis. Minimum data registration period: 1 year. Empowering occupants through periodic communications, to achieve the sustainability goals of buildings.
ID+C	Commercial Interiors Retail Hospitality		Design for Active Occupant	C	1 Credit
					Improve the health of building users through physical activity. Requirement: Buildings must have at least one stairway that allows occupants to move between floors.
BD+C	New Constructions Major Renovations Core and Shell Data Centres Hospitality Retail Schools Warehouses and Distribution Centres		Occupant Comfort Survey	C	1 Credit
					Administer at least one occupant comfort survey, to collect anonymous responses regarding at least the following: acoustics, building cleanliness, indoor air quality, lighting, thermal comfort. The responses must be collected from a representative sample of building users representing at least 30% of the total occupants. At a minimum, administer one new survey at least once every 2 years.

Table 13. POE Criteria in BREEAM v. 2014

TYPE	BUILDING	CATEGORY	CRITERION	C/P	DESCRIPTION
Communities Infrastructure New Construction In-Use Refurbishment & Fit-Out	New Constructions	Management - Man 05 “After-care”	Post-Occupancy Evaluation	C	1 Credit
	Refurbishment & Fit-Out				The client or the occupant of the building undertakes to carry out a post-occupancy evaluation (POE) one year after the initial occupation of the building. The client or the occupant of the building undertakes to carry out adequate dissemination of information on the post-occupancy performance of the building.

Table 14. POE Criteria in WELL v.2

TYPE	BUILDING	CATEGORY	CRITERION	C/P	DESCRIPTION
User and Professional Communities, New Construction and In-Use, Shell and Core	All projects	Community Category	Prerequisite Occupant Survey	P	Prerequisite
					This prerequisite criterion requires that projects collect feedback from users on wellbeing and health within the building. The survey can be provided by third parties (IWBI approved) or can be customized. The survey must be administered to the occupants at least once a year, personal data is guaranteed by privacy and the results are shared with the WELL community online.
			Enhanced Occupant Survey	C	3 Credits
					This feature requires the collection of data from building occupants related to their health and wellbeing and other topics relevant to WELL, both before and during occupancy.

Table 15. POE Criteria in GREEN MARK v. 2005

TYPE	BUILDING	CATEGORY	CRITERION	C/P	DESCRIPTION
Residential and non-Residential Buildings (new or existing)	All projects	Other Green Requirements	Post-Occupancy Evaluation	C	2 Credits
					Post-occupancy survey for users focusing on the performance of the building. There is a minimum number of respondents of 10% and at least 5 people must be interviewed if the total number of building occupants is lower than 50.
					1 Credit
					Creation of a list of strategies of intervention undertaken after the Post-Occupancy Evaluation.

Table 16. POE Criteria in GREEN STAR v. 2003

TYPE	BUILDING	CATEGORY	CRITERION	C/P	DESCRIPTION
New Construction In-Use Refurbishment & Fit-Out	All projects	Indoor Environmental Quality	Occupant Satisfaction	C	4 Credits
					This credit rewards the assessment of the overall perceptions of comfort among building occupants through a survey, with points awarded where at least 80% of respondents indicate satisfaction during the period under analysis.

4.5.1 LEED V.4.0

LEED, or Leadership in Energy and Environmental Design, is one of the most widely used green building rating systems in the world. Available for virtually all building, community and home project types, LEED provides a framework to create healthy, efficient and cost-saving green buildings [Altomonte and Schiavon, 2013].

The LEED building certification system is constituted by a flexible framework that allows design and construction groups to evaluate the strategies that can optimize the relationship between the building and the surrounding environment. The LEED rating system is structured in different sections and organized in prerequisites and credits. The prerequisites of each section are mandatory; the credits can be chosen based on the characteristics of the project. The level of certification is related to the sum of the credit scores. The sections that make up LEED include those listed below:

- Location and Transportation: rewards decision-making on building location, with credits that encourage compact development, alternative transportation, and connection with amenities;
- Sustainable Sites: this section deals with the environmental aspects related to the site within which the building is built and its relationship with the surrounding area. The objectives are to limit the impact generated by construction activities, by controlling rainwater flows, and stimulating methods and construction techniques that respect the balance of the ecosystem, etc.;
- Water Efficiency: this section approaches environmental issues related to the use, management and plumbing of water in buildings, by monitoring the efficiency of water flows, promoting the reduction of consumption water, reuse of rainwater, etc.;
- Energy and Atmosphere: this section promotes the improvement of the energy performance of buildings and the use of energy from renewable and alternative sources;
- Materials and Resources: in this area, environmental issues related to the selection of materials, the disposal and the reduction of waste, transport, etc., are taken into consideration;
- Indoor Environmental Quality: this section deals with the quality of the internal environment, including issues of health, satisfaction, safety and comfort of building occupants;
- Innovation: this section aims to identify the design aspects that stand out for their innovation and application of sustainability practices in the construction of buildings;
- Regional Priority: this area aims to encourage design teams to focus attention on environmental features that are unique to the location of the project.

The sum of the credit scores determines the certification level of the building. Out of a maximum of 110 points available in the LEED system, projects need to obtain at least 40 to be awarded the basic rating. The certification levels are articulated on 4 awards according to the score that is obtained:

- Platinum: over 80 points;
- Gold: 60-79 points;
- Silver: 50-9 points;
- Base: 40-49 points.

Under the Indoor Environmental Quality category, the credit Occupant Comfort Survey awards 1 credit for the administration of at least one occupant comfort survey to collect anonymous responses regarding at least the following:

- Acoustics;
- Building cleanliness;
- Indoor air quality;
- Lighting;
- Thermal comfort.

The responses must be collected from a representative sample of building occupants making up at least 30% of the total occupants. It is also necessary to develop a corrective action plan to address comfort issues and to implement it, if the results indicate that more than 20% of occupants are dissatisfied. At a minimum, one new survey should be performed once every 2 years.

Under the Innovation category, the Occupant Engagement criterion awards 1 credit based on feedback on consumption, implementing methods to inform occupants of energy consumption levels within the building or workspace. This can be achieved in real time or on a monthly basis. There is a minimum occupancy requirement of 1-year. The credit also involves raising occupant responsibility, implementing programmes to involve the occupants through communications that will contribute to the achievement of the sustainability objectives for the building. Performance results should be traced and documented for the occupants through meetings, specifying the areas for improvement and the performance that is achieved. The Design for active occupants (only for existing buildings) criterion awards 1 credit for improving the health of building users through physical activity. Buildings must have at least one staircase that allows occupants to move. Moreover, at least 7 out of the following 11 pre-set design strategies must be included in the project:

- Classify floors to allow occupants regular access;
- Make the stairs visible from the corridor (transparent glass on the doors), stairs not closed;
- Provide accessibility to an open staircase for at least half of the occupants;
- Locate a main staircase to be visible from the main lobby;
- Locate a main staircase to be visible from each floor entrance/vertical circulation;
- Install lighting fixtures on staircases and at each floor;
- Provide daylight using skylights or windows;
- Place signs to encourage the use of health stairs;
- Use inviting sensory stimulation on the stairwells;
- Provide health and exercise equipment for the occupants;
- Provide a multipurpose space to act as on-site exercise room.

For LEED O+M Schools and Homes Multi-Family, this criterion also includes provision for a recreational space and for gymnastic equipment for daily exercise.

Further information available at: https://new.usgbc.org/leed

4.5.2 LEED V.4.1

The categories under which the LEED v.4.1 tool is structured are essentially the same as in version 4.0, although some sections have been modified with respect to the previous version. LEED v4.1 Building Operations and Maintenance (O+M; total points 100) is used for buildings that are operational and have been occupied for at least one year. LEED 4.1 for Building Design and Construction (BD+C; total points 110) applies to buildings that are new construction or major renovations. LEED 4.1 for Interior Design and Construction (ID+C; total points 110) focuses on interior spaces fit-out. For BD+C and ID+C, at least 60% of the gross floor area of the project must have been completed by the time of certification.

Under the Innovation category, the Occupant Comfort Survey awards 1 credit for the administration of at least one occupant comfort survey every two years, for collecting anonymous responses regarding IEQ aspects. The Occupant engagement criterion awards 1 credit for informing the occupants of the actual energy consumption of the building, in real time or through reporting mechanisms on a monthly basis. A minimum data registration period of 1 year is required. Empowering occupants through periodic communications to achieve building sustainability goals is an attempt to improve building performance by enabling energy-efficient behaviour. The Design for active occupants criterion awards 1 credit if buildings have at least one staircase that allows occupants to move between floors, and if the projects respond to a series of pre-set design strategies.

Further information available at: https://new.usgbc.org/leed-v41#bdc

4.5.3 BREEAM V.2014

BREEAM is an international green building rating tool that provides independent third-party certification of the sustainability performance of individual buildings, communities and infrastructure projects. Assessment and certification can take place at different stages throughout the building life cycle, from design and construction through to operation and renovation. Third-party certification involves the evaluation of a building or project by a qualified and licensed BREEAM Assessor to ensure that it meets the quality and performance standards of the scheme. At the heart of this process are rating bodies – organizations with government approval (through national accreditation bodies) – that certificate products, systems and services. The main output from a certified BREEAM assessment is the rating, reflecting the performance achieved by a project, as measured against the standard and its benchmarks (max. 150 credits):

- Outstanding: >85% score;
- Excellent: >70% score;
- Very Good: >55% score;
- Good: >45% score;
- Pass: >30% score;
- Unclassified: <30% score.

BREEAM measures sustainable values under a series of categories, including: Energy, Health and Wellbeing, Innovation, Land Use, Materials, Management, Pollution, Transport, Waste, Water. Available BREEAM tools include: Communities, Infrastructure, New Construction, In-Use, Refurbishment and Fit-Out.
Under the New Construction and Refurbishment and Fit-Out, the category Management - Man 05 Aftercare awards 1 credit for fulfilling the Post-Occupancy Evaluation criterion. The client or the occupant of the building is requested to carry out a POE one year after the initial occupation of the building. This is done to get feedback by the occupants on building performance in use, to inform them of operational processes, including re-commissioning activities, and to maintain or improve productivity, health, safety and comfort. The POE is carried out by an independent third party and must include:

- A review of the design intent and of the construction process (e.g., revision of the design, procurement, construction and delivery processes);
- Feedback from a wide range of building users.

The client or the occupant of the building also undertakes to carry out adequate dissemination of information on the post-occupation performance of the building. This is done to share good practices and lessons learned and to inform of changes in user behaviour, building processes, operating procedures and system checks.

Further information available at: https://www.breeam.com/

4.5.4 WELL V2

WELL v2 builds on the pioneering foundations of WELL v1, drawing from its community of users and professionals, as well as from researchers and health and construction experts around the world. The main objective in the development of WELL v2 was to create a single version of this building standard that could evolve to meet the needs of any type of building anywhere in the world. It was achieved by reaffirming and relying on scientific evidence for effective health interventions within built spaces and organizational practices, referring to the essential elements of what a healthy building must be and introducing new options for what a healthy building could be. WELL is a tool currently used in over 30 countries. WELL v2 consolidates previous iterations and pilot projects in a single instrument for all project types. The system is designed so that system specificity can grow and adapt over time to different design interventions and geographical areas, and in response to new evidence and the constant evolution of public health imperatives.
There are ten concepts in WELL v2: Air, Water, Nourishment, Light, Movement, Thermal Comfort, Sound, Materials, Mind and Community. The credits (Features) can be either preconditions or optimizations. WELL

v2 operates on a point-based system, with a total of 110 points available for each project. All optimizations have a maximum point-value determined by their potential impact. All parts in the optimizations maintain a point value equal to or lower than the maximum optimization. Projects must reach all the prerequisites and a certain number of optimization points to obtain different levels of certification:

- WELL Platinum certification: 80 points;
- WELL Gold certification: 60 points;
- WELL Silver certification: 50 points.

Projects must earn at least two points per concept (or, in the case of the Air and Thermal Comfort concepts, at least four combined points). Each project cannot pursue more than 12 points per concept and no more than 100 points in total among the ten concepts. Projects can also pursue another 10 points for Innovation. At the time of submission for documentation review, projects must present a scorecard that contains a selection of points and features in accordance with these rules.

Under the Community category, the prerequisite C03 Occupant Survey requires that projects collect feedback from users on wellbeing and health within the building. The survey can be provided by one of the IWBI (International WELL Building Institute) pre-approved parties or be customized, and must be administered to the occupants at least once a year. The Enhanced Occupant Survey feature requires the collection of an exhaustive spread of information from building occupants related to their health and wellbeing and other topics relevant to WELL, both before and during occupancy. The requirements include the following:

- For offices (max. 1 point): with 10 or more employees, use pre-approved surveys with one or more specific add-on modules listed on the IWBI website. These surveys will examine consumption, basic occupant data, occupant satisfaction, health and wellbeing, etc. The data must be communicated annually via WELL online and published;
- For all spaces (max. 1 point): with 10 or more employees, the designers manage a pre-occupancy survey, pre-approved, with the basic data of the occupants, the completion of which is mandatory for all occupants. The data will be transmitted to WELL online;
- Monitor survey responses (max. 1 point): improve satisfaction strategies for survey responses;
- Facilitate interviews (max. 1 point): conduct interviews annually to explore the wellbeing of the occupants through qualified personnel. The data must be sent annually to WELL online.

Further information available at: https://www.wellcertified.com/

4.5.5 CROSSWALKS AND ALIGNMENTS

Crosswalks and Alignments are devised to identify synergies and equivalence rules between WELL v.2 and other building certification systems, in order to perform a double assessment of buildings that meet those requirements. Currently, Crosswalks and Alignments are available between WELL v2 and LEED, BREEAM, Green Star, GIGA, and the Living Building Challenge. Crosswalks are based on the following definitions:

- E (Equivalent): when the level of compliance of the external building certification system is considered equivalent, the credit responds to the requirements of WELL;
- A (Aligned): when the credits are aligned but the requirements do not completely overlap. In this case, it is necessary to present reports and evidence to support the award of the credit.

4.5.6 LEED V4.0 AND WELL V2

The correspondence between the WELL v2 and LEED v.4.0 O+M credits requires the LEED Occupant Comfort Survey credit to be aligned (A) with the WELL Select Project Survey requirement. The LEED and WELL surveys have different question categories. WELL requires submission of aggregate survey data through WELL online.

4.5.7 GREEN STAR AND WELL V2

The Green Star's Occupant Satisfaction Survey credit is equivalent (E) to the WELL Select Project Survey prerequisite. It is only valid if the projects use recognized surveys (e.g., CBE, BOSSA, BUS, etc.), otherwise it is considered aligned (A). Furthermore, the survey data must be communicated annually to IWBI. The Green Star's Occupant Satisfaction Levels credit is aligned (A) with the WELL Pre-Occupancy Survey and Report Results credit.

4.5.8 BREEAM AND WELL V.2

In the Aftercare category, the BREEAM's Post-Occupancy Evaluation credit is aligned (A) with the WELL prerequisite Select Project Survey. The BREEAM and WELL surveys have different question categories and requirements for frequency of administration.

Further information available at: https://standard.wellcertified.com/well-crosswalks

4.5.9 GREEN MARK

The Green Mark assessment program was launched by the Building and Construction Authority (BCA) of Singapore in January 2005 to promote environmental sustainability in building design and construction and to foster awareness among industry stakeholders The Green Mark certification system awards a maximum of 140 points for residential and 190 points for non-residential buildings based on a range of environment-friendly criteria. The programme evaluates both new and existing building to measure their performance under the following categories:

- Energy Efficiency;
- Water Efficiency;
- Environmental Protection;
- Indoor Environmental Quality;
- Other green features.

Certified Green Mark buildings are required to be re-assessed every 3 years to maintain their status. Before beginning the assessment process, developers and government agencies have to submit an application form to BCA. The assessment includes design and documentary reviews as well as site verification. The ranking is as follows:

- Green Mark Platinum (90 and above);
- Green Mark Gold (75 to 85 points);
- Green Mark Gold Plus (84 to 90 points);
- Green Trademark Certificate (50 to 75 points).

For Existing Buildings, under the category Other Green Requirements, 3 credits are awarded for the Post-Occupancy Evaluation criterion. More specifically:

- 2 credits for post occupancy surveys. There is a minimum number of respondents of 10% and at least 5 people must be interviewed if the total building occupants are lower than 50;
- 1 credit for the creation of a list of good actions undertaken after the Post-Occupancy Evaluation.

Further information available at: https://www.bca.gov.sg/greenmark/green_mark_buildings.html

4.5.10 GREEN STAR

Green Star, developed by the Green Building Council of Australia, is a certification system under which a building is awarded a rating by an independent third-party panel through a documentation-based assessment. Green Star project evaluations are under nine categories: Management; Indoor Environment Quality; Energy; Transport; Water; Materials; Land Use and Ecology; Emissions; and, Innovation. The Green Star overall rating scale includes the following levels:

- 75+ points: Six Stars – World Leadership;
- Score 60-74 points: Five Stars – Australian Excellence;
- Score 45-59 points: Four Stars – Best Practice;
- Score 30-44 points: Three Stars – Good Practice;
- Score 20-29 points: Two Stars – Average Practice;
- Score 10-19 points: One Star – Minimum Practice.

Under the Indoor Environment Quality category, the Occupant Satisfaction criterion requires the assessment of thermal comfort, acoustics, indoor air quality, lighting and other issues relevant to the comfort and health of building occupants. A maximum of 4 credits are awarded, if at least 80% of respondents indicate satisfaction during the performance period.

Further information available at: https://new.gbca.org.au/green-star/rating-system/

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4.7 ANNEX 1: EXAMPLE OF POE MEASURING SHEET

Building Name:

Monitoring sheet : Participant : Date: Time:

Building Plan

Room Plan

Floor:
Orientation:
Office: Area:

N

- Windows:	Yes ☐	No ☐
- Operable windows:	Yes ☐	No ☐
- Operable blinds:	Yes ☐	No ☐
- Thermostat control:	Yes ☐	No ☐
- Task lighting:	Yes ☐	No ☐

Other observations:
....
....
....
....

Temperature °C	D.B 1		D.B 2		D.B 3		Globe	
	Ground		Ceiling		Front wall		Right wall	
					Entrance wall		Left wall	
Humidity %	H1		H2		H3			
Air speed m/s	AS1		AS2		AS3			
Lighting lux	EV Horizontal 1		EV vertical (facing screen)		EV vertical (facing occupant)		Photo mapping	
	EV H 2		EV VS 2		EV VO 2		PM2	
	EV H 3		EV VS 3		EV VO 3		PM3	
Acoustics dB	dB 1		dB 2		dB 3			
Photos	Photo1 number		Photo2 number		Photo3 number			

4.8 ANNEX 2: EXAMPLE OF A RIGHT NOW SURVEY FORM

Participant Number	
Date	
Time	
Weather Conditions	

What is the current external?				
Air temperature	Relative humidity	Air speed	Hor. illuminance	Sound level

Please complete the following personal details					
Age					
Sex					
State of Health	Ill		Generally OK		Extremely good
How many years have you lived here	<1	Between 1 and 2	Between 2 and 8	Between 9 and 15	Since born

Which of the following climates describes your country of origin before coming to UK?				
Tropical moist	Dry	Moist mid-latitude with mild winters	Moist mid-latitude with cold winters	Cold climate

Have you consumed any of the following in the last 15 minutes?				
Hot drink	Caffeinated drink	Snack or meal	Cold drink	Cigarette

Is your current location close to:	
Perimeter wall	
Partition wall	
Window	
Door	
Source of heat (e.g., radiator)	

What have you been doing in							
	Sleep (0.7 met)	Read (0.8 met)	Seat, relaxed (1.0 met)	Seat, typing (1.1 met)	Standing relaxed (1.2 met)	Walking about (1.7 met)	Walking 2mph (2.0 met)
The last 10 minutes							
The 30 minutes before that							
The 60 minutes before that							

What are you wearing today?		
Walking shorts, short-sleeve shirt	0.36 clo	
Typical summer indoor clothing	0.50 clo	
Knee-length skirt, short-sleeve shirt, sandals	0.54 clo	
Trousers, short sleeve shirt, socks, shoes	0.57 clo	
Trousers, long sleeves shirt	0.61 clo	
Knee-length skirt, long-sleeve shirt	0.67 clo	
Sweat pants, long-sleeve sweatshirt	0.74 clo	
Jacket, trousers, long-sleeve shirt	0.96 clo	
Typical winter indoor clothing	1.0 clo	
Long-sleeve sweat shirt, long-sleeve shirt, trousers, socks	1.14 clo	

Right-Now Survey

Building:........................... Floor:............ Room :.............. Monitoring n.: .... Participant n.: ....

1. Temperature

T1. How best would you describe the temperature in your workspace at the moment?

Too cold ☐ ☐ ☐ ☐ ☐ ☐ ☐ *Too hot*

T2. What is the degree of control that you have over the temperature of your workspace?

No control ☐ ☐ ☐ ☐ ☐ ☐ ☐ *High control*

2. Lighting (Natural/Artificial)

a) Natural

L1. How best would you describe the quantity of natural light in your workspace at the moment?

Far too little ☐ ☐ ☐ ☐ ☐ ☐ ☐ *Far too much*

L2. What is the degree of control that you have over the natural lighting at your workspace?

No control ☐ ☐ ☐ ☐ ☐ ☐ ☐ *High control*

L3. Are you experiencing discomfort with natural lighting in your workspace at the moment?

No discomfort ☐ ☐ ☐ ☐ ☐ ☐ ☐ *A lot of discomfort*

If you are experiencing discomfort with natural lighting in your workspace, please describe where the discomfort is coming from:

b) Artificial

L4. How best would you describe the quantity of artificial light in your workspace at the moment?

Far too little ☐ ☐ ☐ ☐ ☐ ☐ ☐ *Far too much*

L5. What is the degree of control that you have over the artificial lighting in your workspace?

No control ☐ ☐ ☐ ☐ ☐ ☐ ☐ *High control*

L6. Are you experiencing discomfort with artificial lighting in your workspace at the moment?

No discomfort ☐ ☐ ☐ ☐ ☐ ☐ ☐ *A lot of discomfort*

If you are experiencing discomfort with artificial lighting in your workspace, please describe where the discomfort is coming from:

3. Sound/Noise

S1. How best would you describe the level of noise in your workspace at the moment?

Far too quiet ☐ ☐ ☐ ☐ ☐ ☐ ☐ *Far too loud*

S2. How best would you describe your satisfaction with noise at the moment?

Very dissatisfied ☐ ☐ ☐ ☐ ☐ ☐ ☐ *Very satisfied*

S3. What is the degree of control that you have over the noise in your workspace?

No control ☐ ☐ ☐ ☐ ☐ ☐ ☐ *High control*

4. Ventilation and Air Quality

V1. How best would you describe the ventilation in your workspace at this moment?

Very still ☐ ☐ ☐ ☐ ☐ ☐ ☐ *Very draughty*

V2. How best would you describe the air quality in your workspace at this moment?

Very stuffy ☐ ☐ ☐ ☐ ☐ ☐ ☐ *Very fresh*

V3. What is the degree of control that you have over the ventilation in your workspace?

No control ☐ ☐ ☐ ☐ ☐ ☐ ☐ *High control*

5. General comments

Please describe any other issues related to the comfort in your workspace or building overall:

Thank you for your time and cooperation

5 CASE STUDIES

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CONTENT

5.1 CASE-STUDY COLLECTION METHODOLOGY

The methodology conducted to collect the case studies consists of the following phases: (1) determination of the initial premises to search the case studies; (2) development of a template to include the information of each case study; and, (3) identification of the search tools used to collect the case studies.

Case studies incorporating technologies aimed to improving the indoor environment quality were collected on the basis of the following premises:

- Type of buildings: the typologies of collected buildings followed the classification as provided in the introduction, i.e.: residential, office, education, lodging and retail/service.
- Type of technologies: the case studies collected should contain at least one technology designed to improve the indoor environment quality. Technologies can cover a wide range of possibilities, such as materials that reduce indoor contaminants and equipment that improves the indoor comfort.
- Key Performance Indicators (KPIs): as defined in Chapter 2, i.e.: indoor air quality; hygro-thermal environment; visual environment; acoustic environment; and, human values.

Once the initial premises were established, a template to include the information on the case studies was developed. Based on the previous templates elaborated within the COST action RESTORE (by WG1 and WG3), this template was adapted to both the aims and the needs of the case studies repository we are presenting here. The final version of the template included characteristics relating to cultural habits, local climate, a description of the various types of technology in use, etc. It not only includes general information on the building and the technologies, but also more detailed numerical information on the indoor environment and its performance.

The first page of the template (Figure 20) shows the title of the case study, a picture and a general description of the building with some technical data. Information regarding the KPIs which are addressed in the case study is then identified with a tick alongside the relevant KPI. On the left-hand side of the document, some key information of the case study is highlighted, such as: the location and climate zone, the building typology and the sustainability level. At the end of the page, the first technology is presented by indicating the name of the product and a general classification of whether it is a passive, active or control technology. The description of the technology continues on the second page (Figure 21) where the reasoning behind the choice of this technology is explained in a brief justification. In this section, numerical values for the KPIs indicated in the first page are included (if available). Moreover, a detailed description of technology is included as well as information on the positive-negative dependencies to other parameters and the deficiencies or research gaps for further improvements. Finally, potential providers of the technology are indicated. On the left-hand side of the second page, information is included on the client, project team, completion year and awards. More technologies can be included in the template by duplicating the section describing the first technology.

Rethinking technology through case studies
Restore Cost Action WG4.1.F

RESTORE
REthinking Sustainability
TOwards a Regenerative Economy

LOCATION
(incl address, GPS or Lat Lon so we can map)

CLIMATE ZONE
(according to KFICAT)

BUILDING TYPOLOGY
(color and highlight the correct one)

- **R** Residential
- **O** Office
- **E** Education
- **L** Lodging
- **RS** Retail/Services

SUSTAINABILITY LEVEL
(Optional - Please give your opinion about the sustainability level)

- **C** Conventional — *Building as usual*
- **S** Sustainable — ***Limiting impact.*** *The balance point where we give back as much as we take*
- **RS** Restorative — *Restoring social and ecological systems to a healthy state*
- **RG** Regenerative — *Enabling social and ecological systems to maintain a healthy state and to evolve*

Name of the Building

Photo credits

General description of the building. Text 3-4 sentences

TECHNICAL DATA

Gross area: XXXX sqm

Key performance indicators (KPIs) *(Please tick ✓ the KPI's which are addressed in the case study)*

INDOOR AIR QUALITY	
Contaminants – % of Formaldehyde	✓
Outdoor/Indoor - Particulate matter: PM10 / PM2.5	
Occupants satisfaction - % satisfied people	
HYGRO-THERMAL ENVIRONMENT	
Temperature/humidity/air speed - Standard Effective Temperature (SET)	✓
Occupants satisfaction - % satisfied people	
VISUAL ENVIRONMENT	
Daylight - Daylight factor (DF)	
Occupants satisfaction - % satisfied people	
ACOUSTIC ENVIRONMENT	
Background noise level - Noise criteria (NC)	
Occupants satisfaction - % satisfied people	
HUMAN VALUES	
External view and Right to light - % workstations with windows access	

REGENERATIVE TECHNOLOGY #1

GENERIC NAME/PRODUCT NAME

Classification of the technology: Passive/Active/Control

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1

Figure 20. Case study template. Page 1

Rethinking technology through case studies
Restore Cost Action WG4.1.F

RESTORE
REthinking Sustainability
TOwards a Regenerative Economy

CLIENT / OWNER / INVESTOR
(include the client OR building owner OR investor)

PROJECT TEAM
(name)

COMPLETION YEAR
(year)

AWARDS
(Include any certificates, prizes, etc. If not applicable, delete the section)

Effects/improvements on indoor environment of the case study
Please justify in one or two sentences why this technology was chosen in the project. For example, to improve indoor air quality, reduce heat loss, energy saving, etc. Add data regarding the % of improvement *(coming from the technology: climate, living, user behavior, materials, durability, maintenance, ...) In addition, if available, please add numerical values for the KPIs indicated above. If more than one technology is used, the general improvements or numerical KPI values of the case study can be incorporated above (in the general description of the building).*

Sustainability level: Regenerative/ Restorative/ Sustainable/ Conventional

Detailed description of technology: Max. 100 words. You can include information about the composition, appearance, dimensions, drawings, calculations, etc.

STRENGTH MEASURE OF EFFECTS *(optional if available)*
Max. 100 words. You can include information about the positive-negative dependencies to other parameters, state of pareto-optimality, other reconditions for effect achievements, appropriate for Building Certification System, ...

STRENGTH-WEAKNESS ANALYSIS OF THE TECHNOLOGY
(optional if available)
Max. 100 words. (Superiority of the technology relative to conventional ones, deficiencies, research gaps for further improvements, limits according to current state of technology, ...)

Possible providers of technology: Include one or two manufacturers, executers, etc.

REGENERATIVE TECHNOLOGY #2

GENERIC NAME/PRODUCT NAME

If more than one technology is used, please complete this section as done above. Add as many sections as needed. If not applicable, delete the section.

ACKNOWLEDGEMENTS
One or two sentences maximum. If not applicable, delete the section.

LINKS AND REFERENCES

Please note that the document should not exceed 3 pages

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2

Figure 21. Case study template. Page 2

Finally, a call to collect case studies was issued and circulated to all the RESTORE participants as well as to the trainees attending the Training School organized in Venice (December 2019).
Case studies were collected using the personal experience of each RESTORE participant and their direct contact with the industry. In addition, several platforms and online tools were also used to collect case studies:
Build up platform: http://www.buildup.eu/en/practices/cases
Living-future map: https://maps.living-future.org/

5.2 OVERVIEW OF CASE-STUDY COLLECTION

An overview of a collection of 36 case studies is provided in Table 17. Most of the case studies are in Europe, but some are also from Asia, North and South America. No case studies were collected from either Africa or Australia.
At an earlier stage, it was decided to create an Atlas or a repository Map to present information on collected case studies. The great advantage of a map rather than lists and tables is that the geographic location of individual cases may be visualized, clearly indicating their distribution. When additional filters are applied, it further facilitates the quick search for information of interest. It was decided to use free tools from Google My Maps and Google Earth to create the Atlas. The Atlas is accessible as an online platform embedded in the RESTORE website (https://www.eurestore.eu/).
A comprehensive .xls/.csv file was compiled from the information in previously completed case-study templates. This file serves as a source database to create the Atlas or the repository Map. It was decided to include the following information: name and location of the building, climate zone, building typology, sustainability level, information on client/owner/investor, project team, completion year as well as relation to KPIs. The information regarding the KPIs which are addressed in a case study is identified by assigning a binary Yes/No value to each of the KPIs. More descriptive information of the building itself and the technologies it employs are not included in the Map source file. They are still accessible via the Map (Figure 22), as each placemark is linked to the appropriate form that provides further details, links and references.
Several filters (grouping) were applied to the Map to facilitate further differentiation in terms of the parameters that are considered important when analysing solutions for the regenerative environment, namely building typology, sustainability level and 5 KPIs (Figure 23):

- Grouping case studies by building typology into 5 groups: Residential, Office, Education, Lodging and Retail/Services
- Grouping case studies by sustainability level into 4 groups: Conventional, Sustainable, Restorative and Regenerative
- Grouping case studies into 2 groups (Yes/No) for each of the 5 KPIs identified: (1) Indoor Air Quality; (2) Hygro-Thermal Environment; (3) Visual Environment; (4) Acoustic Environment and (5) Human Values. Thus, those case studies that are related to a certain KPI may be easily distinguished on the Map.

Table 17. Overview of collected case studies

No.	Name	Location	Year	Build. Typ.1	Sust. Level2	Technologies				
						IAQ3	HTE4	VE5	AE6	HV7
1	Semi-detached house	Barajas, Spain	2014	R	S	N	Y	N	N	N
2	Art Gallery-Cultural centre	Nottingham, UK	2008	RS	S	N	N	Y	N	N
3	The Edge - office	Amsterdam, The Netherlands	2014	O	S	N	Y	Y	N	Y
4	Agencia Andaluza	Sevilla, Spain	2013	O	S	N	Y	Y	Y	N
5	François Mitterrand High School	Brasilia, Brazil	2016	E	S	N	Y	Y	N	Y
6	Live Work Home	Syracuse, USA	2010	R	RS	N	Y	Y	Y	N
7	The Research Support Facility	Golden, USA	2010	E	RG	N	Y	Y	N	N
8	Manitoba Hydro Place HQ	Winnipeg, Canada	2009	O	C	N	Y	Y	N	Y
9	B+A House	Skopje, North Macedonia	Under cons.	R	RG	Y	Y	Y	Y	Y
10	Apt. Building with Wood-Polymer Windows	Zürich, Switzerland	2012	R	S	N	Y	N	N	N
11	Ed70 Ciemat Building	Madrid, Spain	2008	O	S	Y	Y	Y	N	Y
12	NZEB Medical centre	Lodosa, Spain	2019	O	S	Y	Y	N	N	Y
13	ZEB LivingLAB	Trondheim, Norway	2016	R	RS	Y	Y	Y	Y	N
14	NZEB 29 dwellings	Pamplona, Spain	2017	R	S	Y	Y	N	N	N
15	WeEBuilding	R. de Pena, Portugal	2016	R	S	Y	Y	Y	Y	N
16	Nursery School and kindergarten CASANOVA	Bolzano, Italy	2017	E	RS	Y	Y	Y	N	Y
17	Prismian HQ	Milan, Italy	2017	O	RS	N	Y	Y	N	Y
18	Aulario IndUVA	Valladolid, Spain	2018	E	RS	Y	Y	Y	N	N
19	Villa Castelli - Italy	Bellano, Italy	2015	R	RS	N	Y	N	N	N
20	Solar XXI	Lisbon, Portugal	2006	O	S	Y	Y	Y	Y	Y
21	Dynahaus	Halbergmoos, Germany	2014	R	RS	Y	Y	N	N	N
22	Ca' Foscari - Palazzo	Venice, Italy	2014	O	C	Y	Y	Y	Y	Y
23	Hungarian Nest +	Szentendre, Hungary	2019	R	S	Y	Y	N	N	N
24	Rokko Shidare Observatory	Kobe, Japan	2010	RS	RG	N	Y	Y	N	N
25	Greenpeace Spain Headquarters	Madrid, Spain	2019	O	RS	Y	Y	N	N	N
26	CERC Boldesti-Scaeni	Boldești-Scăeni, Romania	2015	E	RG	Y	Y	N	N	N
27	VP22	Milan, Italy	2021	O	RG	Y	N	Y	N	Y
28	Detached house	Prishtina, Kosovo	2016	R	RS	Y	Y	Y	N	Y
29	National Headquarters E.ON ROMANIA	Tg. Mureș, Romania	2015	O	S	N	Y	N	N	Y
30	CopenHill	Copenhagen, Denmark	2017	RS	RG	Y	Y	N	N	Y
31	Espacio itdUPM	Madrid, Spain	2016	O	RS	N	Y	N	Y	N
32	Bullitt center	Seattle, USA	2013	O	RG	Y	Y	Y	N	Y
33	Copenhagen Tower Buildings 405-406	Copenhagen, Denmark	2015	O	S	N	Y	N	N	Y
34	Liko – Vo	Slavkov u Brna, Czech Republic	2019	RS	RG	N	Y	Y	N	Y
35	Administrative Building	Skopje, North Macedonia	In cons.	O	S	Y	Y	Y	Y	Y
36	70 Wilson	London, UK	2016	O	RS	Y	Y	Y	N	Y

[1] Build. Typ.=Building Typology: R=Residential; O=Office; E=Education; L=Lodging; RS=Retail/Services;
2 Sust. Level=Sustainability Level: C=Conventional; S=Sustainable; RS=Restorative; RG=Regenerative;
3 IAQ=Technologies for Indoor Air Quality; 4 HTE=Technologies for Hygro-Thermal Environment; 5 VE=Technologies for Visual Environment;
6 AE=Technologies for Acoustic Environment; 7 HV=Technologies for Human Values

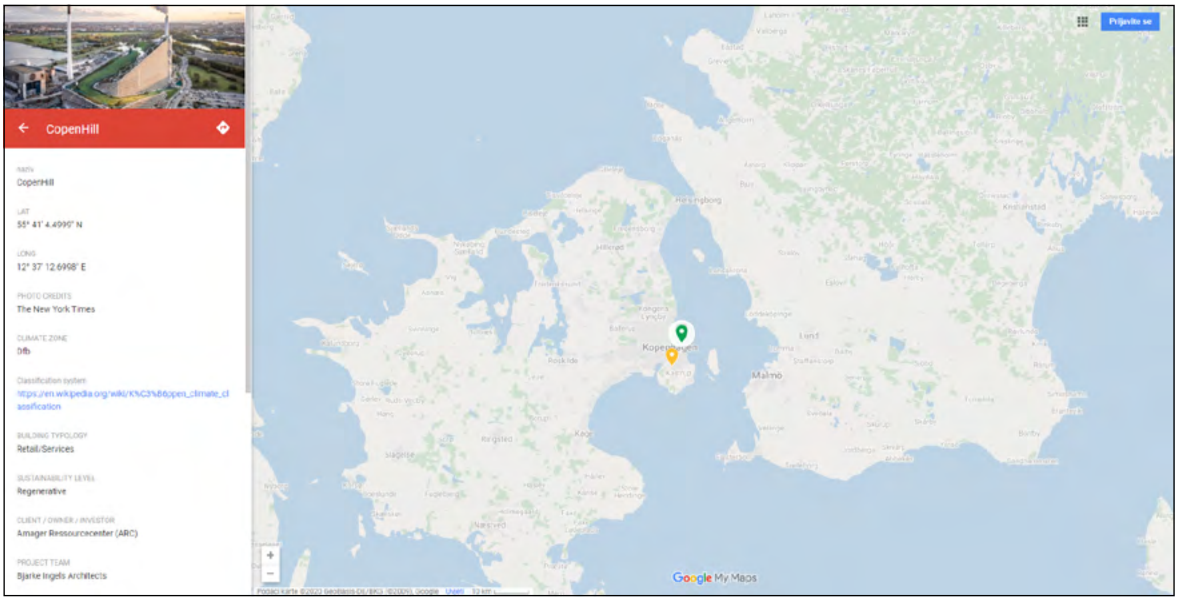

Figure 22. An example of more detailed information with further links for a case-study provided in the Map representation

Figure 23. Distribution of case studies depending on sustainability level

The map was created using Google My Maps. Members of the public interested in accessing the map may do so through the interactive map on the COST RESTORE website https://www.eurestore.eu/. In addition, data from the map were transferred in a .kmz file that can be downloaded for viewing through locally installed Google Earth Pro applications or with Google Earth online, which requires no local installation. In the case of the Google Earth, a layer was added containing the world map of the Köppen-Geiger climate classification, version March 2017 (.kmz file with medium resolution, available from http://koeppen-geiger.vu-wien.ac.at/present.htm) (Figure 24).

The placemarks for both Google My Maps and Google Earth were positioned with the latitudinal/longitudinal data provided by the author(s) of each case study. In several cases, the exact location was not disclosed – so the placemark points to a wider location (generally city centre) with an appropriate note that it is an approximate location. For some case studies 3D building views are available (Figure 25).

Figure 24. Case study mapping in Google Earth

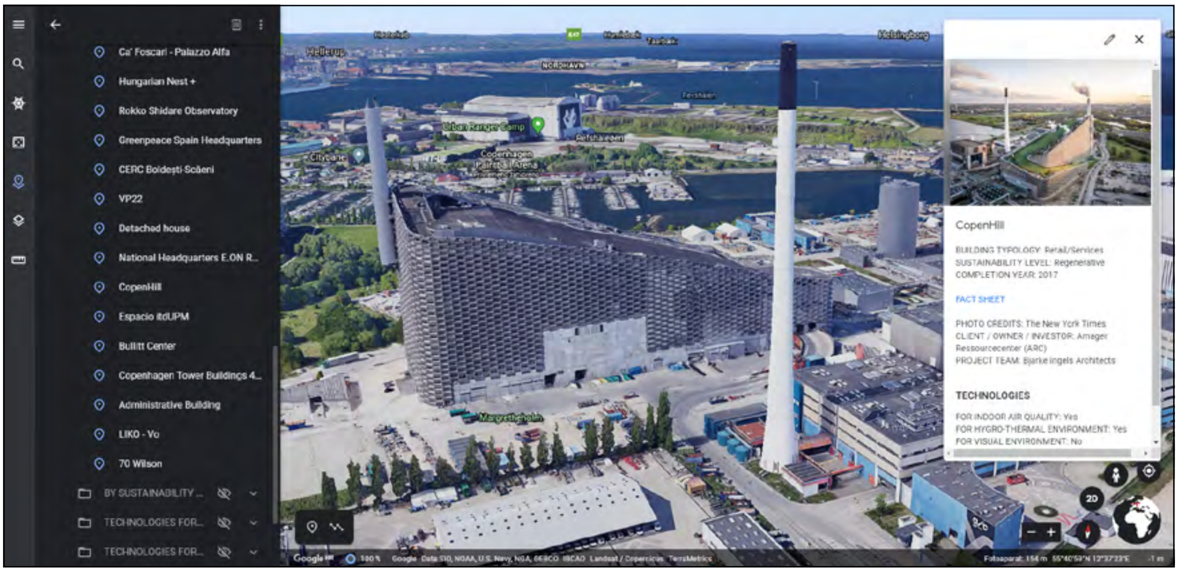

Figure 25. 3D building view of a case study in Google Earth

5.3 STATISTICS

The collection of case studies is accompanied by some statistical results, which summarize the main features of the template in use and include, among others, the types of building, the sustainable level and the year of completion. More importantly, statistical results related to the types of technology applied in the collected case studies were categorized as follows: technologies for indoor air quality, technologies for hygro-thermal environments, technologies for visual environments, technologies for acoustic environments and technologies related to human values. The analytical results are discussed in the following paragraphs.

5.3.1 GENERAL STATISTICAL DATA

Figure 26 shows the statistical information on building types from the case-study collection. The information shows that Office buildings represented 44% and are the type of building where technologies are most often applied for indoor air quality improvement. The second most popular case-study was on Residential buildings, representing 31%, and the third most popular selection was Educational buildings, representing 14%. In contrast, Retail/service buildings are the types of buildings with the least involvement in the application of technologies for indoor air quality improvement. Lastly, the Lodging type of buildings option does not appear in any of the collected case studies.

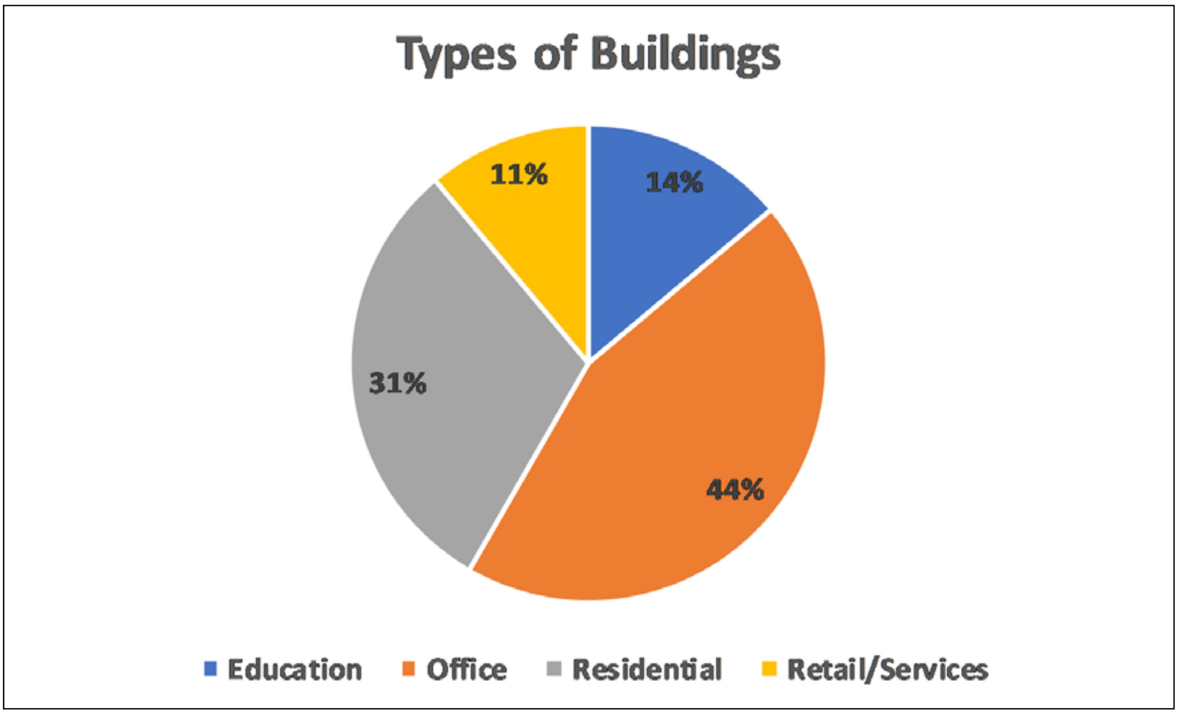

Figure 26. Results of statistical data on the types of buildings that apply technologies for indoor air quality improvement from the case-study collection

Figure 27 shows the statistical information on the Sustainability levels taken from the collection of case studies. The results showed that the Sustainable and the Restorative levels, respectively representing 42% and 31%, were the sustainable levels that the users selected most often in the evaluation of their case studies. The third most popular level, Regenerative, represented 22% of the levels that were selected. Lastly, 5% of the responses were characterized as Conventional.

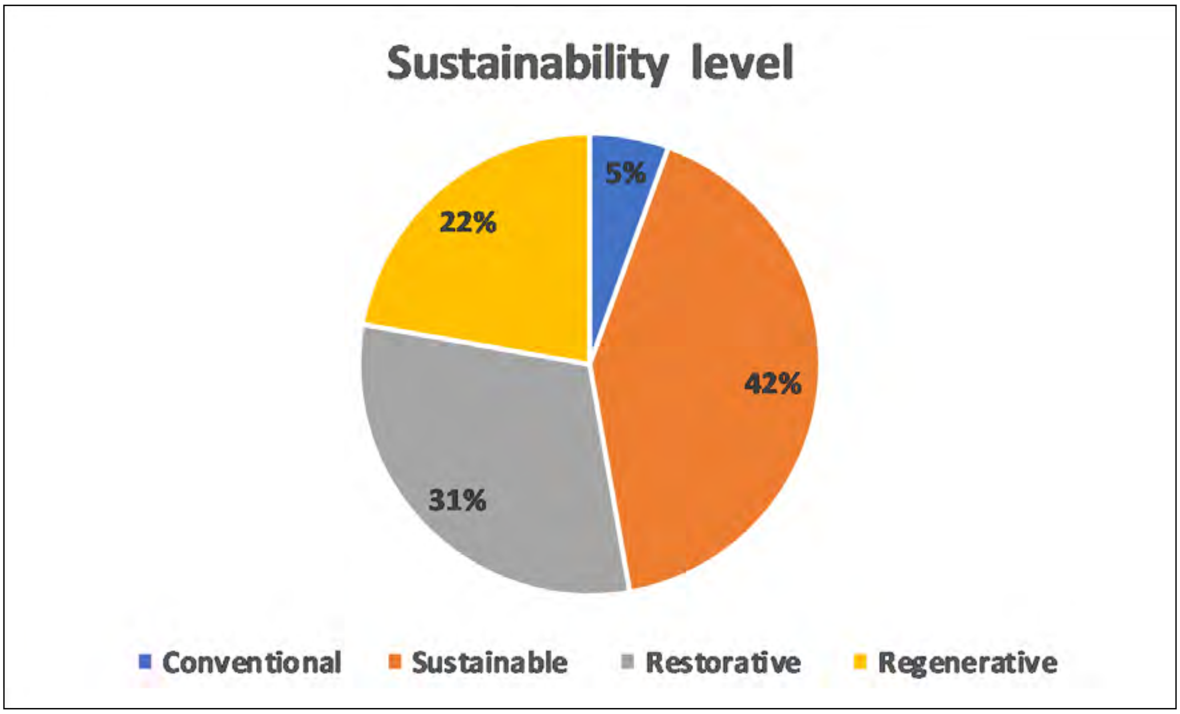

Figure 27. Results of statistical data on the Sustainability level of each case study from the case study collections

Figure 28 shows statistical information from the collection of case studies regarding their Year of completion. In this case, the results showed that the vast majority of cases were completed between 2011-2020 with some case studies, still under construction, representing 81% of the statistical results. The second most popular answer regarding the year of completion was the period between 2001-2010. Information on case studies completed before the Millennium year, 2000, are not provided.

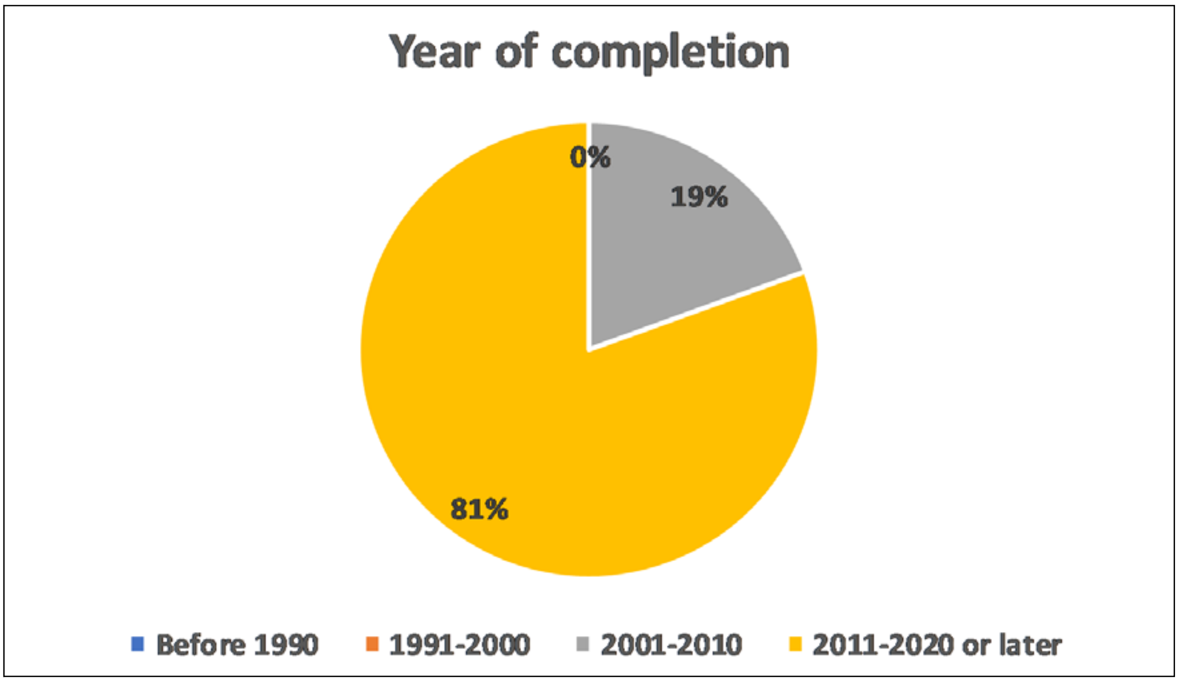

Figure 28. Results of statistical data on Year of completion for each case study from the collection.

5.3.2 TECHNOLOGIES

Figure 29 shows a bar chart of the total number of technologies applied in the selected case studies for indoor air quality, hygro-thermal environments, visual environments, acoustic environments and human values. The results showed that the most frequently applied technologies were the improvement of the hygro-thermal environment, and the second most popular technologies were for improving the visual environment. The technologies for improving the indoor air quality were in third place, while the technologies for human values and improvements to the acoustic environment occupied the final two places.

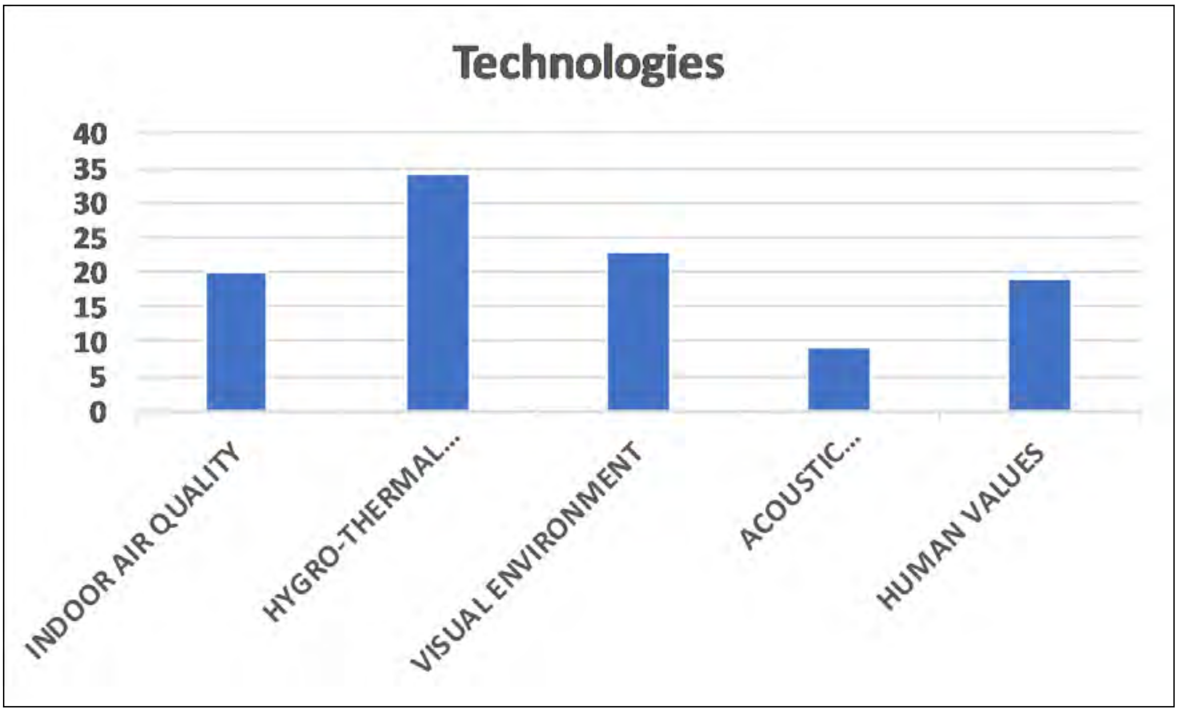

Figure 29. Type of technologies applied in the collected case studies

5.3.3 LESSONS LEARNT

The case studies that were received were then analyzed in terms of their sustainability level, building type, year of completion, and the types of technology they incorporated, to find ways of improving their indoor air quality. It was concluded that a considerable number of the case studies were characterized as sustainable and restorative, and fewer as regenerative. Also, the Atlas of case studies presents a large number of contemporary buildings, built since 2011, over the past nine years.
In addition, office buildings mainly incorporate technologies for the improvement of their indoor air quality, while educational, retail/service and lodging buildings still needed to enhance the use of similar or new technologies, if they were to reach similar levels of indoor air quality. Architects and designers need to consider regenerative technologies when designing their work, specifically in education, retail/service and lodging buildings, if they are to extend the range of technologies, implementing them for the improvement of indoor air quality in those categories of buildings and others, and achieving a transition from the sustainable to the regenerative level.
Finally, while the majority of the technologies are applied with the aim of improving both the hygrothermal and the visual environments, further investigation towards the development and the application of technologies designed to improve acoustic environments and human values should be promoted, in order to extend their implementation in buildings and to achieve regenerative sustainability.

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6 SOLUTION-SETS FOR A REGENERATIVE ENVIRONMENT

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CONTENT

6.1 INTRODUCTION

In the field of regenerative design, several interrelated, innovative building concepts are now challenging the traditional building paradigm and even present-day standards for sustainable design, by introducing the idea of buildings as more dynamic and interactive structures. These include the concepts of living, regenerative, restorative, and adaptive building components. In this way, these technological solutions can be defined as multifunctional highly adaptive systems, where the physical separator between the interior and exterior environment can change both its functions and its features and behaviour over time, in response to transient performance requirements and boundary conditions, with the aim of improving the overall building performance [Romano, Aelenei, Aelenei, and Mazzucchelli, 2018] protecting people from hazards and helping them access such resources as food, water, and shelter [Gambato and Zerbi, 2019]. Finally, within the principles of biophilic design, which is "the theory, science and practise of creating buildings inspired by nature, with the aim to continue the individual's connection with nature in the environments in which we live and work every day" [Kellert, Heerwagen, and Mador, 2011], it is important to develop solutions that are imbued with positive emotional experiences, in their shape, form and dimensional design. The previous chapters have defined the characteristics of regenerative indoor environments, the environmental aspects contributing to the achievement of such goals, as well as the Key Performance Indicators (KPIs) that will be used to assess the efficacy of the solutions. The question addressed in this chapter is how those performance levels can be achieved. More specifically, the chapter will provide advice and guidelines on the technological solution-sets that designers might apply to achieve a regenerative indoor environment. After a first definition of the main environmental aspects under consideration and the functions of the building that will be considered, the general framework for the collection of information on the various technological solutions available on the market will be presented. In the second part of the chapter, several technical solutions will be presented, which are grouped into the three main building systems: building envelope, interior elements and finishes, and active systems (Heating, Ventilation and Air Conditioning (HVAC), renewable energy systems (RES), and controls). Finally, the integration of technical solutions previously identified as suitable for achieving the regenerative goals will be discussed. Within these scenarios, examples of integrated solutions designed by trainees attending the 4th COST RESTORE Training school, held in Venice, between the 2nd and the 5th of December 2019, will be summarized and discussed.

6.2 THE FRAMEWORK OF THE SOLUTIONS-SETS

A specific framework for the collection of the solution-sets to achieve the regenerative environment goal has been created. The framework is a means of establishing the links between the environmental aspects, their sub-aspects, the functions required by the building systems and components to perform, in order to achieve the goals, and the related technologies that can be applied. Table 18 provides an overview of these links between environmental aspects and sub-aspects and the functions of the building systems and their components. It has to be highlighted that, in accordance with the goals of the Restore COST Action WG4, the analysis has mainly been focused on technologies suitable for office buildings and five main environmental aspects. However, the way in which the framework was designed also means that researchers and practitioners can also implement solutions-sets for other building types (e.g., residential and commercial or educational buildings) and/or increase the number and the typology of environmental aspects under consideration. the five environmental aspects in our analysis have been described in the previous chapters of the booklet (i.e. indoor air quality, hygro-thermal environment, visual environment, acoustic environment, human values). Within the indoor air quality aspect, sub-aspects related to contaminant concentrations, outdoor/indoor interaction, and occupant satisfaction have been analyzed in detail. The related functions of the building, its sub-systems and components that fulfil the performance requirements are as follows: the capacity either to remove or to absorb pollutants; the capacity to change the air; and, the capacity to control the concentration of pollutants and contaminants. The information on technologies affecting the hygro-thermal environment aspects, the visual environment, and the acoustic environment were collected by focusing both on the objective and the subjective factors. The objective factors under consideration are air temperature, relative humidity and air speed for the hygro-thermal environment, the daylight availability for the visual environment, and the background noise levels for the acoustic environment. The subjective factors are, instead, always related to occupant satisfaction levels. The following functions of the building are needed to achieve the environmental goal: the hygro-thermal environment can be controlled by means of active and passive strategies; the visual environment can be controlled by either blocking solar radiation or facilitating its entry into the building. Finally, the acoustic environment can be controlled by means of two concurrent strategies: prevention and absorption of sound and noise.

*Table 18. **The relation between environmental aspect, performance sub-aspects and building functions***

Environmental aspect	Sub-aspect	Function
Indoor air quality	Contaminants	Remove/absorb pollutants Change air Control
	Outdoor/Indoor	
	Occupant satisfaction levels	
Hygro - thermal Environment	Temperature/humidity/air speed	Passive/active
	Occupant satisfaction levels	
Visual Environment	Daylight	Allow/block light and sun
	Occupant satisfaction levels	
Acoustic Environment	Background noise level	Prevent noise Absorb noise
	Occupant satisfaction levels	
Human Values	External view and Right to light	Allow view and light Include natural elements within the space
	Biophilia	

The last environmental aspect that has been analyzed is the one related to human values. Among the large amount of human values to be integrated into building design, we have selected the two having the highest relation with regenerative design principles: external view and right to light, enabled by means of the presence of a view towards the outside and natural light within indoor spaces, and biophilia, enabled by the inclusion of natural elements, such as plants, within the space.

It must be noted that a technology may achieve more than one function, which can be, at the same time, a holistic, regenerative design applied to more than one component of the building. For example, according to the "Attention Restoration Theory" [Kaplan and Kaplan, 1989], elements of "soft fascination" such as light breezes or other natural air movements can be provided, to improve user concentration. Therefore, an effective restorative approach will supply combinations of ambient and surface temperatures, humidity and airflow, similar to those experienced outdoors, while also providing some form of personal control (e.g., manual, digital, or physical relocation) over those conditions [Browning, 2014]. These functions can only be achieved by integrating technologies for the different sub-systems of the building, including the building envelope, interior elements, building services and controls. To that end, the solution-sets are organized within a framework that connects the environmental aspects, the functions and the sub-systems. Within this scope, three main building sub-systems are analyzed: the building envelope, the interior elements and finishes and the active building systems (comprising HVAC, RES and controls). In the following paragraphs, each of the three sub-systems are better described in detail.

6.2.1 BUILDING ENVELOPE

Regenerative building envelopes can be defined as technological bio-based solutions, inspired by nature, adaptive, and capable of interacting with the external environment and user requirements to improve indoor

comfort [Kuru, Oldfield, Bonser and Fiorito, 2019]. In addition, they are not only able to restore, but also to improve the surrounding natural environment by enhancing the quality of life for biotic (living) and abiotic (chemical) components of the environment [Nugent, Packard, Brabon and Vierra, 2016].
Several different types of regenerative envelope systems have already been developed, and an increase in emerging, innovative solutions is expected over coming years. However, when referring to adaptive technologies, two main categories can be distinguished: 1) adaptive technologies, which rely on passive design to improve indoor comfort and building energy efficiency; and, 2) active technologies that include renewable harvesting [Mazzucchelli, et al., 2018].
The regenerative building envelopes must be able to control one or more of the environmental aspects, as indicated in Table 18. For example, it should prevent the entry of contaminants from the exterior, for good indoor air quality, while ensuring adequate thermal resistance to address the required hygrothermal performance. Moreover, the openings of the building envelope will affect the visual and the acoustic environment. These must positively influence health, wellbeing and quality of life through building envelope solutions that follow natural patterns and features. The current knowledge base of biomimetic properties is growing rapidly and will very likely result in a surge of new product development with enormous biophilic and restorative design implications.

6.2.2 INTERIOR ELEMENTS AND FINISHES

Several scientific studies have shown that we spend most of the day inside the buildings where we work and live. However, many researchers have demonstrated that environmental pollution within the internal space is often much higher than it is outside [Jones, A.P., 1999]. Great attention must therefore be paid to the design and the selection of interior elements (materials and furniture), choosing natural and eco-compatible ones, in order to reduce the environmental impact of the built environment and to improve indoor comfort.
In addition, to decreasing user stress, it is important to create indirect experiences within the building, involving contact with nature that requires on-going human input, such as views of the nature, shapes, forms, patterns and a colour palette that feels connected to nature, together with natural light, live plants, greenery and water features. It has been shown [Appleton, 1996] that users react positively to head-on exposure with the natural environment, and they also respond with a degree of certainty to the artificial imitation of nature and its forms in fractal patterns, as well as to cases of organic and conceptual mimicry of natural entities.

6.2.3 ACTIVE BUILDING SYSTEMS (HVAC/RES/CONTROLS)

Indoor thermal comfort is an important factor when designing healthy and sustainable buildings. In the framework of regenerative design, thermal comfort must be achieved primarily through a proper control of thermal fluxes within the building envelope, and secondly through a well-designed and efficiently operated HVAC system [Konstantinou and Prieto Hoces, 2018]. While it logically appears best to keep indoor conditions constant, several studies have shown that performance in a work or school setting is enhanced within spaces with thermal variability and clean airflows. Clean indoor airflow stimulation has been found to keep people awake, also naturally improving focus and performance. There are several passive (e.g., natural ventilation, envelope shape, window coatings and manipulators) and active (e.g., HVAC delivery) ways to create the variability of natural spaces within the building. An integrated design combines both strategies to create variability, especially because most environments are unable to use solely natural methods, due to impracticality. For example, natural ventilation has its limits in very high temperature, high humidity or high pollution periods, which has led to development of mixed-mode cooling and ventilation HVAC systems [Kellert et al., 2011].
Mixed-mode HVAC supports the use of both natural and mechanical ventilation, decreasing building energy consumption through the reduction of mechanical fan use and, in some cases, the cooling demands (e.g.: by night cooling). Furthermore, they provide a means of removing and absorbing pollutants and can control CO_2 levels, without producing noise. Over past years, many innovative HVAC systems (e.g.:

Ice-Powered Air Conditioning; DeVAP Air Conditioning; etc.] have been up marketed in the construction market to reduce consumption on building energy.
Moreover, regenerative buildings need to be designed as nearly zero energy and nearly carbon neutral buildings. In other words, regenerative buildings have to produce all or part of the renewable energy necessary to meet their energy requirements (heating, cooling, electricity, hot water, etc.). They have to be designed, so that their carbon footprints are minimized across their entire life cycle span. The objective is the on-site production of the renewable energy (e.g., from: PV or solar thermal panels; geothermal pipes; dual fuel pumps; etc.) to power the HVAC equipment and to integrate some of its components (e.g.: heat pipe-heat exchanger; heating storage; vents; etc.) within the building envelope, in order to transform the whole building into an interactive organism capable of both reacting in a dynamic way with the external environment and, at the same time, satisfying the user requirements. Additionally, these buildings must provide on-site energy storage for added resilience.
Finally, since comfort (visual, thermal and acoustic) is inherently subjective, and strongly varies from person to person, it is important to give occupants a degree of control, which can be architectural in form (e.g., access to operable windows or shades) or mechanical (e.g., access to localized and energy-efficient fans or heaters, and thermostat controls).

6.3 TECHNICAL SOLUTIONS

As previously explained, one of the goals of the Restore WG4 was to survey the existing building technologies and identify those contributing to the regenerative environment goal. Therefore, the framework described in the previous paragraph was used to collect information on both existing technologies and their contribution to the environmental aspects and functions that have previously been described. It may be noted that one technology might affect more than one environmental aspect or might show more than one function. For this reason, at the end of the current paragraph, we have included a sub-paragraph on the integration between functions and between sub-systems, showing how the database of solutions can also be used to understand the interrelation between sub-systems, from the perspective of an holistic integrated design approach. The database of solution-sets was compiled, starting with known cases of existing or new technology and several working group members of Restore WG4, as well as the trainees of the 4th Restore training school also made contributions. Moreover, some of the solutions come from the case studies described in the previous chapter of the book. The database is meant to be a free tool, accessible to both the scientific and the technical community, which can be continuously updated with new information. At the time these guidelines were drawn up, about 50 technical solutions had been analyzed. They are almost equally spread among those referring to the building envelope sub-system, to active system components, and to the interior sub-system and building finishes. In the following sections of this paragraph, the technical solutions that have been collected are analyzed for each individual sub-system: building envelope, interior elements and finishes, and active systems.

6.3.1 BUILDING ENVELOPE

Table 19 details the technologies that refer to the building envelope sub-system. At the time of the drawing up this manual, 17 solutions had been analyzed. As can be seen from the table, most (over 80%) of the solutions offer a means of influencing the hygro-thermal environment, with the indoor thermal comfort control as the most relevant aspect. The acoustic environment (70% of solutions) is the second most affected environmental aspect, and the reduction of noise transmission is the most relevant aspect that is controlled. All the other 3 aspects are controlled in almost the same number of cases (35%-45%).

In summary, the solutions collected for regenerative envelopes are designed to react to changes from external factors, in order to promote restorative sustainability for the built environment in the following ways:

- Removing/absorbing pollutants that could accumulate inside the buildings (e.g.: green façade; double-skin façades; photocatalytic components; etc.);
- Encouraging natural ventilation by reducing energy consumption for summer air conditioning (e.g.: operable windows; double-skin façades; wind towers and wind directional chimneys; etc.);
- Maximizing direct solar gains by fitting extensive glass surfaces with high thermal insulation (e.g.: double-skin façades; thermally activated glass facades; regenerative PCM-façades; solar tube and/or shed windows and solar greenhouses; etc.);
- Controlling the glare effects and providing protection from solar radiation in summer (e.g.: high-tech shading-systems; thermally activated glass façades; etc.);
- Reducing the transmission of noise from the exterior to the interior and the reverberation effect within the internal spaces (e.g.: green walls and roofs; double-skin façades; straw bale building envelopes; clay walls, rammed-earth façade elements; envelope systems insulated with materials that are provided with ecological and toxicological certification; etc.);
- Increasing natural lighting and allowing the view of natural elements by creating transparent openings of suitable sizes (e.g.: double-skin façades and solar greenhouses).

Table 19. Overview of technologies for the building envelope

Building envelope	Indoor air quality		Hygro-thermal environment			Visual Environment				Acoustic Environment				Human Values	
	Remove/absorb pollutants	Change air inthe room	Hygro-thermal control	Indoor thermal comfort	Passive building performance	Solar radiation control	Glare reduction	Block light and sun	Allow light and sun	Reduce reverber-ation	Reduce the noise transmission	Prevent noise	Absorb noise	Allow view and light	Natural element
Green wall, Vertical garden, green roof,	X			X	X		X				X	X	X	X	X
High-tech shad-ing-systems				X			X								
Operable windows		X	X	X	X	X	X		X		X			X	X
Smart opaque envelope	X	X	X	X	X						X				
Double skin facades	X	X	X	X	X	X	X		X		X			X	X
Photocatalytic envelope system	X														
Straw bale build-ing envelope			X	X	X						X		X		
Rammed-earth façade elements			X	X	X						X		X		X
Prefab, straw bale façade			X	X	X						X		X		X
Insulation materi-als ecologically, toxicologically certified			X	X	X					X	X		X		
Thermally activat-ed glass façade				X		X	X	X	X						
High thermal in-sulation thickness			X	X	X						X		X		
Regenerative PCM-Facades			X	X	X	X	X	X	X		X				
Solar tube and or shed window			X	X					X						
Wind tower, di-rectional chimney	X	X													
Solar Greenhouse	X								X		X			X	X
Acoustic, façade panel with micro-drilling			X	X	X					X	X		X		

Basic envelope solutions that we can find in regenerative buildings are green façades, green walls and/or green roofs. These bio-based technological solutions provide an additional layer of insulation that can protect buildings from heavy rainwater, help manage heavy storm water deluges, and provide thermal mass. They also help reduce the temperature of a building, because vegetation absorbs large amounts of solar radiation. Furthermore, these can decrease building energy demands and, at the same time, cleanse the air from VOCs (Volatile Organic Compounds) released by paints, furniture, and adhesives, which can cause asthma and allergies. In addition, vegetation in green walls can help with the mitigation of the heat island effect and contribute to urban biodiversity [Gunawardena, Wells and Kershaw, 2017].

Other technological solutions that are useful to achieve the target of regenerative environment are those in which innovative materials (e.g., photocatalytic coatings, PCM, TIM, etc.) are integrated, which can purify the air, both inside and outside the building, and exercise smart control over the hygro-thermal, visual and acoustic environments.

Many studies, experimentations and test campaigns at international research centres and enterprises have been performed in the course of developing materials that can mimic photocatalysis, a natural phenomenon similar to photosynthesis, whereby substance known as photocatalysts, through the action of natural or artificial light, trigger a strong oxidation process converting noxious organic and inorganic substances into absolutely harmless compounds. The first opportunity to use photocatalytic cementitious materials occurred in 1996, thanks to the technical sponsor, Italcementi, and the role it played in the realization of Richard Meier's Dives in Misericordia Church, in Rome. In 2015, the same technology was applied to the entire outdoor surface and part of the interior of Palazzo Italia, built in the Milan Expo area. In 2018, an Italian research group developed the double skin façade prototype SELFIE [Gallo and Romano, 2018], where an integrated system made up of ceramic honeycomb panels treated with photocatalytic paint was located inside the air-gap (between the transparent external layer and the opaque internal insulation panel), in order to contribute to air purification in the buffer zone. In all three case studies (Figure 30), the photo-catalytic material was capable of purifying the air, improving the indoor and outdoor comfort parameters.

Double face 2.0 is an example of a façade system, developed using innovative materials, that can be used to regenerate an indoor space with shading devices and an insulation panel. This innovative lightweight translucent Trombe wall (designed from a research group of the Delft University) uses new materials such as Phase Change Material (PCM) for heat storage and aerogel for thermal insulation, has an optimized shape for high thermal performance, is manufactured using robotic 3D (FDM) printing (Figure 31), allows daylight to pass through it, and can be adapted to local conditions and environments. By optimizing and shaping geometry inspired by nature, the final design has good engineering performance and at the same time offers new creative opportunities for the designers, in order to replicate natural patterns within the building [Tenpierik, et al. 2018].

Figure 30. The options of the SELFIE façade [source: Gallo and Romano, 2018]

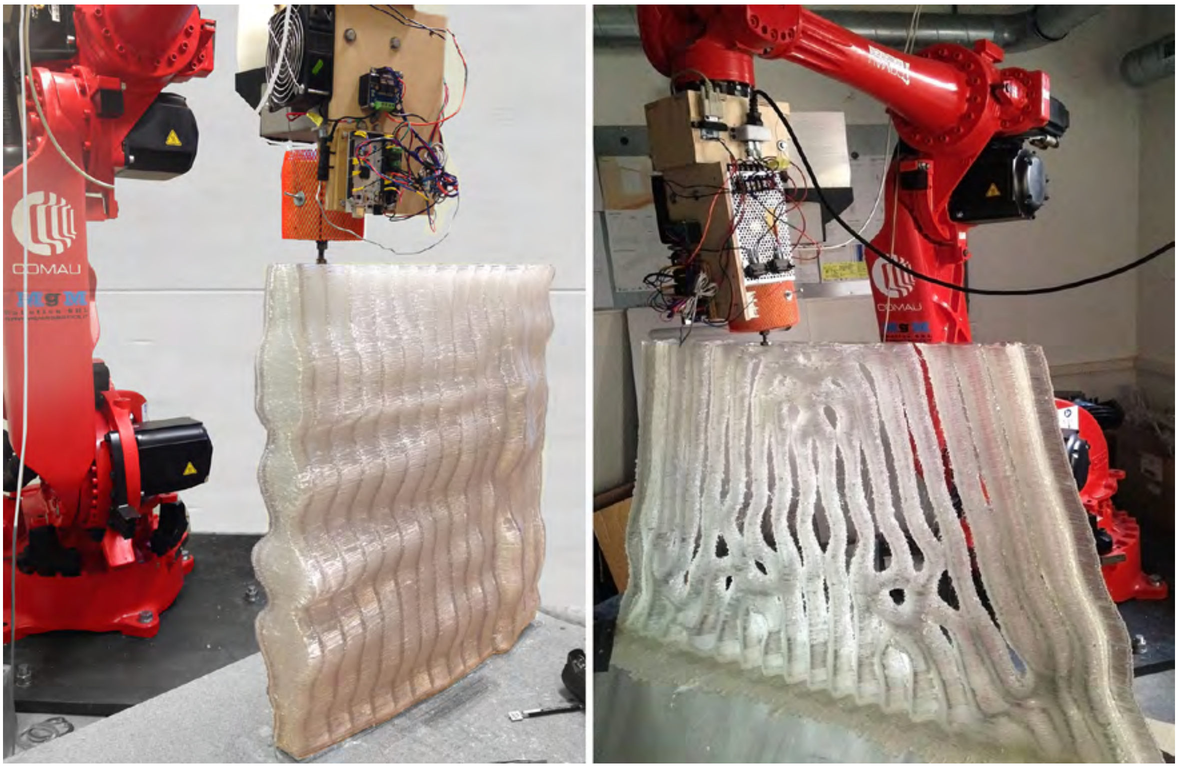

Figure 31. Robotic FDM 3D printing of the Double face 2.0 prototype [source: Tenpierik et al., 2018*].*

Other sustainable envelope solutions that may be integrated into a restorative project are the rammed-earth façade elements. Rammed earth is a longstanding construction technique where natural aggregates – gravel, sand, silt and clay - are compacted into a formwork creating a monolithic building structure. These façade systems have excellent capabilities to maintain stable interior air humidity levels and show thermal mass potential superior to that of most alternative building materials. In addition, over recent years, the growing demand from the public for natural material, beauty and complexity has pushed designers to investigate innovative prefabricated earth and straw bale wall panels, to combine the performance and low environmental impact of traditional natural materials with reduced labour and more consistent results.

Finally, the integration of technological solutions is also important in the design of a restorative building, which can be used to increase natural ventilation, thereby reducing energy consumption for summer air conditioning. It is therefore important to recall the importance of the design components (e.g., operable windows, wind towers and wind directional chimneys) of the envelope that can work with natural air, managing indoor temperature and air quality (e.g.: absence of pollution and CO2). In modern restorative buildings, e.g., wind chimneys and towers, should be employed as primary ventilation drivers, to enhance a low-energy mechanical ventilation system, in the design of atriums and/or glazed facades. These ventilation stacks are, in fact, aerodynamically designed to enhance the wind pressure differences that occur when air flows around obstacles.

6.3.2 INTERIOR ELEMENTS AND FINISHES

Table 20 includes the details of the technologies that have been collected and that refer to the interior elements and finishes. At the time these guidelines were drawn up, 17 solutions had been analyzed. Unlike in the previous section on the building envelope, there is a more even balance of solution-sets that can address and control each of the five environmental aspects. In greater detail, approximately 50% of the technologies under assessment can be used to control hygro-thermal and acoustic environments. Approx-

imately 40%, 35%, and 30% of the technical solutions successfully address the visual environment, human values, and indoor air quality, respectively.
In detail, regenerative interior elements must be able to control one or more of the following environmental aspects:

- Indoor air quality: pollutant removal and/or absorbance (e.g.: green walls; photocatalytic, antibacterial TiO_2 and responsive coatings; interior partitions with plasterboards capable of absorbing contaminants; atrium with plants and natural elements; etc.);
- Hygro-thermal Environment: improving the U value and/or Thermal inertia of the building envelope and the indoor comfort -in terms of temperature and relative humidity- (e.g.: water walls and fountains; green walls; natural and recycled materials; insulating materials with ecological and toxicological certification; etc.);
- Visual Environment: monitoring the solar radiation to decrease the glare phenomena and maximizing the daylighting (e.g.: internal shading devices; solar shelf; drapes, curtains, shades and blinds; daylight provision with a sunlight redirection system with heliostats and fixed mirrors; etc.);
- Acoustic Environment: decreasing the transmission of noise from the exterior to the interior and the reverberation effect within the internal spaces (e.g.: natural and recycled insulating materials; sound-absorbing 3d-printed panels; interior wall and ceiling coverage; etc.);
- Human Values: improving the user psychological perception through the integration of atriums with plants and natural elements (e.g.: water, sounds, and murals inspired by flora and fauna) into the spatial configuration of the building.

Table 20. Overview of technologies for the interior components

Interior Elements	Indoor air quality		Hygro-thermal Environment			Visual Environment				Acoustic Environment				Human Values	
	Remove/absorb pollutants	Change air in the room	Hygro-thermal performance control (Uvalue, Inertia)	Indoor comfort (temperature)	Optimization of passive building performance	Solar radiation control	Reduction of glare phenomena	Block light and sun	Allow light and sun in	Reduce reverberation effect	Reduce the transmission of noise from outside to inside	Prevent noise	Absorb noise	Allow for view and light that Include natural elements	Natural element
Green wall	X		X	X	X		X			X	X			X	X
Water wall/Fountain				X											X
Operable windows															
Natural Materials (e.g., wood, clay plaster, Natural Stone, etc.)			X	X	X					X	X				X
Photocatalytic coating	X														
Recycled material (e.g., slag)			X	X	X						X		X		
Internal shading devices						X	X	X							
Solar Shelf						X	X	X	X						
Drapes/Curtains/ shades/Blinds						X	X	X							
Insulating materials with ecological and toxicological certification			X	X						X	X		X		
Antibacterial TiO2 coating and Responsive Coatings	X														
Interior partitions with plasterboards capable of absorbing contaminants (formaldehyde);	X		X		X						X				X
Interior wall/ceiling coverage			X		X				X	X			X		X
Daylight provision by a sunlight redirection system with heliostats and fixed mirrors									X						
Sound-absorbing 3d-printed panels										X			X		
Atrium with plants and natural elements	X	X		X	X				X		X			X	X
Use of natural sounds and murals inspired by nature.														X	

Whilst outdoor air pollution is important, the potential health effects of poor indoor air quality also need to be considered in the field of restorative design. Poor indoor air quality can have negative impacts on building occupants, particularly for people with sensitivity to pollution and allergies, showing respiratory health conditions. Furthermore, considering that people spend 90% of their time indoors, the effects of poor air quality can range from odour, to irritation, to more serious toxic effects.
Green walls (such as the one shown in Figure 32) -a vertical garden that serves as a natural air purifier, removing VOCs and other harmful toxins while exhaling oxygen into the space as a by-product of photosynthesis- are a useful element that integrate nature within the indoor environment. The green wall also has an evaporative and cooling effect. Studies show that green walls can reduce heat gain by up to 10°C, resulting in significant energy savings, reducing cooling costs and decreasing electricity costs (by up to 20%) [Coma, Pérez, Martorell & Cabeza, 2014]. Plants can also reduce noise levels within buildings, similar to the way in which plants have been used worldwide to reduce noise along roads and highways. Vegetation naturally blocks high frequency sounds while the supporting structure of the wall and its mass help diminish low frequency sounds; together, each element reflects, refracts and absorbs acoustic energy. [O'Grady, 2016].

Figure 32. The interior green wall of the PULSE building of TUDelft, the Netherlands

6.3.3 ACTIVE BUILDING SYSTEMS

Table 21 details the collection of technologies that refer to the HVAC system, the renewable energy systems and the control systems. The totality of all cases (over 90%) that have been collected refer to the hygro-thermal environment, and most of the technologies are also able to control indoor air quality. The acoustic environment is, likewise, influenced by 40% of the technologies, while the visual environment is influenced by about 25% of the solutions. Human values are not so affected by active building systems, and in our survey, we found that in only 2 out of 15 cases was there any influence on that aspect of the regenerative design.
An innovative system to control indoor comfort is the digital ceiling, a prototype from Cisco. This technological component is fitted with a variety of sensors which can detect motion, occupancy, temperature and even carbon dioxide levels. The digital ceiling can control building lighting, security and HVAC systems. The sensors can learn the daily habits of an occupants and automatically adjust air and light settings.

Interior monitoring devices can contribute to improve indoor environmental quality. These systems continuously monitor and assess indoor air quality and adjust it as may be needed. The building management systems (BMS), for example, help building owners to provide occupants with air that is finely adjusted, not only its temperature, but also its humidity, and its CO_2 levels, particulate matter, and VOC exposure, resulting in a space with reduced energy consumption and improved occupant experience, productivity, and wellbeing.

Wireless temperature monitoring systems are considered as a strategy to improve HVAC control in the building, so that temperatures in rooms with different functions can be adjusted intelligently, according to their occupancy, human activities, and specific requirements. Furthermore, these technological solutions can effectively reduce energy consumption during the operation of HVAC systems and maintain appropriate room temperatures to ensure human comfort [Aksamija, 2015].

Moreover, it is evident that a Building Management System (BMS) must be integrated into a regenerative building that can dynamically control temperature, humidity, daylighting, and pollutant concentrations (e.g., CO_2, etc.). Sensors and actuators can be integrated in the building envelopes and interior components, offering smart and kinetic configurations in response to environmental and human requirements. In other words, the regenerative building can be compared to a smart building, provided with artificial intelligence and capable of reacting in an osmotic manner to the weather conditions, in order to balance its comfort performances and energy consumptions. The possibility of dynamic control over the physical parameters (e.g.: temperature, lighting and sound) means that the sensorial experience of users and the human value of the built environments can be improved, which is also a requirement of biophilic and regenerative design theory.

Finally, as highlighted in the previous sections, the integration of RES in regenerative buildings is essential. Despite the traditional systems that are already commonly used in buildings, the survey has recognized the presence in the market of advanced solutions combining two renewable energy sources (e.g., photovoltaic with hydrogen storage) and advanced systems (e.g., systems exploiting bio-hydrogen energy, high temperature solar panels for heating and solar cooling) that can contribute to the restorative goals of producing energy in excess of the amount required for the daily operations of the building.

Table 21. Overview of technologies for the active building systems

Active Building Systems	**Indoor air quality**		**Hygro-thermal Environment**			**Visual Environment**				**Acoustic Environment**				**Human Values**	
	Remove/absorb pollutants	Change air in the room	Hygro-thermal performance control (Uvalue, Inertia)	Indoor comfort (temperature)	Optimization of passive building performance	Solar radiation control	Reduction of glare phenomena	Block light and sun	Allow light and sun	Reduce reverberation effect	Reduce exterior-to-interior noise transmission	Prevent noise	Absorb noise	Allow exterior views and Include natural light	Natural element
Ventilation with heat recovery	X	X		X	X										
Ventilator with heat recovery integrated in window frame	X	X		X	X				X		X	X		X	
Air inlet through green façade/ green house	X	X		X	X										X
Fresh air preheat-ing, e.g., earth duct air	X	X		X	X						X				
Automatic opera-ble windows	X	X		X	X				X		X				
Turbine ventilation fan	X	X		X	X										
Night cooling			X	X	X						X	X			
High temp. solar panels for heating & cooling			X	X	X										
Seed oil fuelled CHP			X	X											
Bio-hydrogen energy			X	X											
PV with hydrogen storage + heat pump - 100% RES house			X	X	X										
Direct current of solar panels within the building					X										
Smart digital ceiling	X	X	X	X	X	X	X				X				
Building Manage-ment Systems (BMS)	X	X		X	X	X	X								
Sound masking solutions										X			X		

6.3.4 RELATION BETWEEN THE SUBSYSTEMS

As explained above, there are clear relations between the subsystems that the design should take into account. The table below provides an overview of those connections, reflecting the conclusions of several exemplary case studies under analysis.

Table 22. The relations between the sub-systems' functions

Subsystems			
Building Envelope	**Interior**	**HVAC**	**Control**
Straw bale building envelope (e.g.: Ricola building, Austria SME, etc), clay wall, Rammed-earth façade elements.	Natural material used as finishes inside the building (bio lime, natural clay plaster, reed panels, etc).	System to replace air inside the room.	BMS with sensors that can control the pollutants inside the building; and open and close the windows when necessary. Sensor in clay wall controls the heating and cooling system.
Insulating materials with ecological and toxicological certification (e.g.: Oeko-Tex standard 100).	Possibility of using recycled materials such as Maiano™ insulation panels) inside the building to control sound and to guarantee good air quality.	HVAC System to control air exchange.	BMS with sensors that can control the pollutants inside the building; and, open and close the windows when necessary.
Façade built with photocatalytic concrete (e.g.: Torre delle Especialidades – Mexico City; EXPO Milan; Padiglione Italia EXPO 2015 Envelope).		Windows integrated with ventilation HVAC System to control air exchange.	BMS with sensors that can control the pollutants inside the building; open and close the windows; switch on the artificial light to guarantee the activation of the photocatalysis process when necessary.
Photocatalytic and antibacterial coating used inside the façade component (e.g., SELFIE).	Interior plasterboard partitions capable of absorbing contaminants (formaldehyde); Interior wall/ceiling coverage.	Windows integrated ventilation system and HVAC System to control air exchange.	BMS with sensors that can control the pollutants inside the building; open and close the windows; and, switch on the artificial light to guarantee the activation of the photocatalysis process when necessary.
Green wall, Vertical garden, Florafelt System, living garden, green roof, Green ground cover.	Green wall, vertical garden, Garden Tower, Florafelt System.		BMS that can control the irrigation system integrated in the component.

6.4 EXAMPLE OF SOLUTION-SET COMBINATIONS

The technical solutions of the framework that has been developed underpin the creation of a regenerative, indoor environment. Moreover, it directs designers towards integrated solution-sets that address different environmental aspects and separate building's subsystems. The decisions over which combinations of technologies to apply and how to use them while designing for a regenerative indoor environment are determined by each specific building context, and the objectives of the project among other parameters. In this section, we will present example combinations of the technologies, which compose solutions sets for a regenerative indoor environment. The example combinations are based on the work of the COST RESTORE WG4 training school.

The training school "Rethinking technologies for regenerative indoor environment" was organized within the framework of the COST Action RESTORE and took place at the University Iuav of Venice on the 2-5th December 2019. About 30 participants from 15 different countries attended and worked on the integration of restorative technologies in the redesign of an existing case-study building located in Mestre (VE). The building, completed in 2014, functions as a facility of the University Ca' Foscari of Venice, designed by Studio Architetti Mar, and it hosts rooms for teaching and student support activities, offices, research spaces and a library, over a total gross floor area of 27,245 m2. The special configuration and site of this building within the landscape marks the boundary between the Venetian mainland and the lagoon surrounding the historic city centre of Venice.

Figure 33. The case-study building Ca' Foscari – Palazzo Alfa, Studio Architetti MAR

A south-facing black structure rises 45 m across nine floors, characterized by a relatively closed configuration, with trapezoidal elevations and ventilated walls clad in horizontal dark grey zinc-titanium panels organized in differently sized bands. On the contrary, the north-facing structure is a more regular-shaped construction that is constituted by seven floors, with glazing and shading systems. The participants were divided into five, multi-disciplinary groups to promote interaction within and between groups. Using the aforementioned framework and input from the COST RESTORE trainers, participants brain stormed different regenerative solution-sets to improve indoor environmental qualities and the function of the case-study building. The intervention objectives and solution-sets are presented below. These solution-sets consist of several technological interventions, addressing different environmental aspects.

6.4.1 RED GROUP: INTEGRATION OF NATURE IN THE BUILDING AND SURROUNDINGS

Participants: Evola Gianpiero, Krezlik Adrian, Magurean Ancuta Maria, Petrov Teodor, Stella Anastasia

Intervention objective: The aim of this design intervention is to improve health, happiness and equity, by integrating elements of the natural habitat and promoting biodiversity, while improving building performance and function.

Solution:

The first element for integration was a green façade on an additional double-skin construction, which addressed the environmental aspects of visual comfort by providing shading and glare reduction, as well as wind shielding, biophilia and rainwater management. The latter two aspects were also enhanced by the introduction of a roof garden, for urban farming and an animal habitat structure, and a green piazza on the ground level. The floorplan was adjusted to be more flexible and the double-skin area improved circulation within the building. Natural material, such as paper waste insulation boards and reclaimed wood are used for the new elements. Photovoltaic panels (PV) on the roof cover 25% of the electricity use. Additional interventions include heat recovery ventilation and Building Management Systems (BMS).

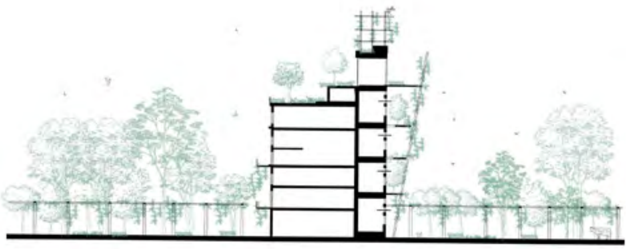

Figure 34. Section and impression of the building, showing the double skin façade addition and the introduction of natural elements.

Summary/overall result:

Environmental aspect	Building Envelope	Interior Elements	HVAC	Controls	RES
Indoor Air Quality	Green Façade	Furniture without formaldehyde	HR mechanical ventilation, Linear slot diffusers	BEMS: screens at floor level make energy	PV panels (21.5 kW, η = 21%)
Hygro – Thermal Environment	Exterior walls, clay plaster, clay bricks, recycled paper insulation, double glazing, timber frame, green façade		Mechanical ventilation with heat recovery (η = 80%), Linear slot diffusers, Heat pumps	BEMS: Temperature divided on spaces for all genders	PV panels (21.5 kW, η = 21%)
Visual Environment	Light shelves (S façade), Green façade (shading)	White ceilings			
Acoustic Environment		Sound absorption ceilings, sound absorbing movable decorations	Technical room provided with acoustic panels, low-noise mechanical ventilation		
Human values	Increase of glazed surfaces% on South façade, Green façade, wild garden				

6.4.2 PURPLE GROUP: RETHINK SECOND SKIN AND BALCONIES

Participants: Fernandes Jorge, Kobas Bilge, Jimanez Pulido Cristina, Vian Silvia

Intervention objective:

In this intervention, improvements to Daylight and Energy Efficiency are addressed, as well as thermal comfort, IAQ and Human Experience.

Solution:

The approach of the solution is to rethink the second skin and balconies, in order to enhance the building's function. The double skin is introduced on the south-east façade, which functions as a solar chimney, improving air movement for ventilation and the removal of contaminants. The solar chimney is combined with elements of passive cooling, including night ventilation and evaporative cooling. A new layout was proposed to increase visibility through the façade, for enhanced views and daylight. Green elements were used at the balconies, together with shading, to control the light. Finally, a green wall was added in a public area and PV panels to the façade.

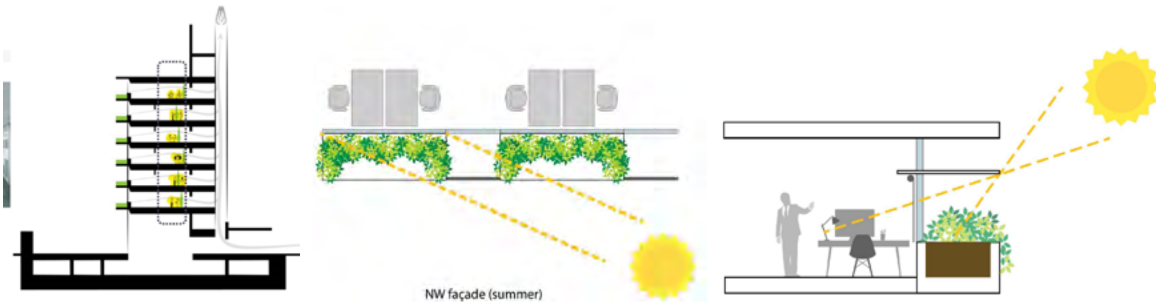

Figure 35. The double facade acts as a solar chimney to enhance air movement and has balconies redesigned with green walls and shading elements.

Summary/overall result:

Environmental aspect	Building Envelope	Interior Elements	HVAC	Controls	RES
Indoor Air Quality		Furniture and indoor elements finishing with low VOC content, Green wall			
Hygro – Thermal Environment	Pool for evaporative cooling, balconies for sun shading		Solar chimney + wind turbines		PV ventilated façade
Visual Environment	Vertical slats to protect from solar radiation.	White & Wood ceilings,		Dimmable sensor operated LED lighting system	
Acoustic Environment		Acoustic panels in the ceiling, carpets on the floor, acoustic partitions			

Environmental aspect	Building Envelope	Interior Elements	HVAC	Controls	RES
Human values	External vegetation in the balustrade	Increased % of workstations with daylight/window access, vegetation on façade			

6.4.3 BLUE GROUP: COLLECTIVE INTELLIGENCE THROUGH SMART MONITORING AND CONTROL

Participants: Avella Francesca, Bessi Alessandra, Iuga Tudor, Martin Simon Sandra, Petrovski Aleksandar

Intervention objective:

The aim is to improve health & wellbeing within the indoor environment, considering acoustic, visual and adaptive conditions, thermal comfort, human values, and air quality. Moreover, the technologies should enable human engagement and awareness.

Solutions:

The interventions are proposed for different scales: green areas and greywater ponds at site level; and, passive solutions at building level, such as thermal storage and passive ventilation, as well as active façades, comprising PV panels and solar thermal systems. Bio-based materials with low embodied energy are proposed as alternatives to standard materials. Finally, the backbone of the intervention is the operation and management system, performed directly by the user, using smart control, user education, and a web platform for building performance data, etc.

Figure 36.The building is user oriented, incorporating individual monitoring and control, to improve performance and user satisfaction.

Summary/overall result:

Environmental aspect	Building Envelope	Interior Elements	HVAC	Controls	RES
Indoor Air Quality	Adaptive façade			Collective intelligence: Monitoring and control	

Environmental aspect	Building Envelope	Interior Elements	HVAC	Controls	RES
Hygro – Thermal Environment	Thermal storage, adaptive façade	Bio-based internal finishing material	Passive ventilation, biophilic design.	Collective intelligence: Monitoring and control	PV panels and solar thermal systems
Visual Environment				Collective intelligence: Monitoring and control	
Acoustic Environment		Bio-based internal finishing material		Collective intelligence: Monitoring and control	
Human values		Bio-based internal finishing material		Collective intelligence: Monitoring and control	

6.4.4 GREEN GROUP: HOLISTIC APPROACH TO REGENERATIVE DESIGN

Participants: Viola Maffessanti, Ferhat Bejtullahu, Marcello Dellipaoli, Sadije Kelmendi, Veronika Petrova, Gurkan Yildrim

Intervention objective:

The following aspects in need of improvement were identified: thermal comfort, daylight, user control, clear outdoor connections, sociality (outdoor entrance), social space.

Solutions:

The strategies that were implemented followed an holistic approach, referring to optimized orientation, form and dimensions, low-impact material selection, façade ratios, shading, active strategies, building from waste, and natural ventilation. An important intervention was the addition of a full height buffer zone, which functioned as a chimney, improving natural ventilation and creating a wider space for social interaction. Vegetation was introduced in the new zone and a green façade on the eastern side, creating biophilia, and humifying and cleaning the air.

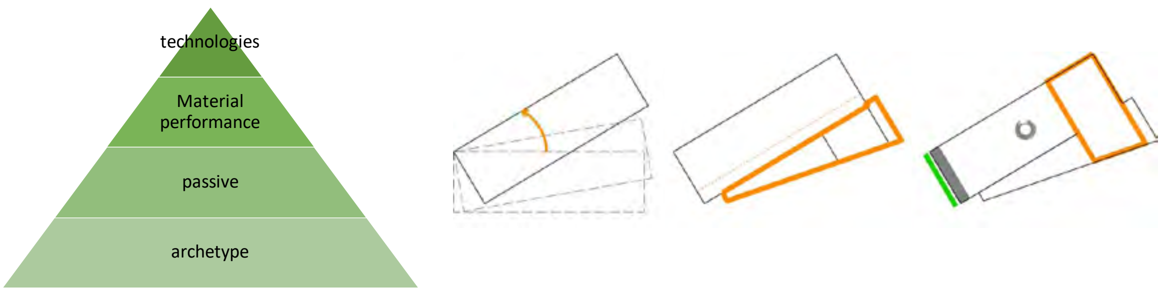

Figure 37. The holistic approach to regenerative indoor environment includes architectural and geometrical characteristics, passive design principles, such as the construction of a thermal buffer, and material performance, such as recyclable materials.

Summary/overall result:

Environmental aspect	Building Envelope	Interior Elements	HVAC	Controls	RES
Indoor Air Quality	Chimney to improve ventilation	Vegetation			
Hygro – Thermal Environment	Orientation (-30deg), green west façade, rammed earth east façade Phase-change materials in north façade	Rammed earth in the auditorium for thermal mass	Shape, solar chimney		PV glass skin on buffer south wall
Visual Environment	Transparent façade of buffer zone for best performance of daylight and visual comfort.				
Acoustic Environment		Rammed earth in the auditorium for thermal mass			
Human values	Wider ground floor space as social space Shape, orientation (-30deg), views to campus plaza and Venice	Main central staircase in the centre Demountable structural elements Bio-based material			

6.4.5 YELLOW GROUP: WELLBEING AS THE STARTING POINT

Participants: Federica Franzé, Francesco Perozzo, Kasimir Forth, Marian Ontkoc, Melinda Orova, and Nestor Rouyet

Intervention objective:

The building needs to be flexible to avoid rapid growth of obsolescence, and to foster a human-centric model, which is focused on the particular health care needs of the individual - people are not only treated from a performative perspective, but also from an emotional, mental, spiritual and social perspective. The proposed intervention should enable this model. The ability to offer feedback and have a recognized stake in one’s comfort and well-being can have a positive impact on occupant mood.

Solution:

The starting point of the intervention is that physical well-being, psychosocial well-being, and neurocognitive wellbeing should be combined. To do so, a restorative space may first be considered or defined by its ambient qualities including light quality, sounds, air quality, and temperature. The solution-set must include interventions that range from the introduction of interior and exterior green elements and walls and urban farming on the roof, to vertical lamellas on façades and Titanium Dioxide Coatings for air cleaning. It must, moreover, include spaces for social interaction on the roof, the stairways and other interior areas.

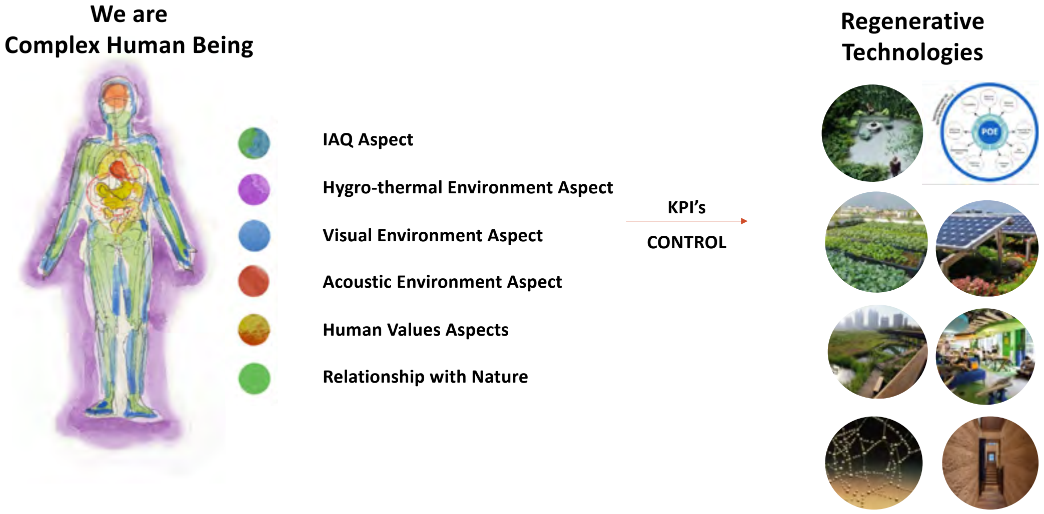

Figure 38. The steps that the regenerative technological solutions follow, starting from the premise that a person is a complex individual, and moving to the evaluation of user needs in compliance with environmental aspects and KPIs. The combination of all these aspects led us to the definition of the regenerative solutions framework.

Summary/overall result:

Environmental aspect	Building Envelope	Interior Elements	HVAC	Controls	RES
Indoor Air Quality	Green roof	Clay plaster, green walls	Titanium coating, green walls		
Hygro – Thermal Environment	Fibre for condensation, green roof, PV / solar collector, phytoevaporation, water collection	Clay plaster, thermal/occupancy zoning – floor plan rearrangement, design manual, promoting stairs, green walls	Thermal/occupancy zoning – floor plan rearrangement, green walls	Thermal/occupancy zoning – floor plan rearrangement	Fibre for condensation, PV / solar collector, phytoevaporation, water collection
Visual Environment	Lamella, titanium coating, green roof, community garden, closed patio	Acoustic – textile doors, reorganizing the floor plan, drinking fountain, circadian lighting, community garden, design manual, promoting stairs			

Acoustic Environment	Green roof, closed patio	Clay plaster, acoustic – textile doors, music, closed patio, green walls			
Human values	Green roof, closed patio, summer cinema	Acoustic – textile doors, thermal/occupancy zoning – floor plan rearrangement, reorganizing the floor plan, drinking fountain, circadian lighting, community garden, design manual, promoting stairs, music, green walls		Thermal/occupancy zoning – floor plan rearrangement, drinking fountain, circadian lighting, POE.	

6.5 CONCLUSIONS

The present chapter has covered the work of the COST Restore Working Group WG4 concerning the collection of technical solutions available to engineers and architects, in order to achieve the regenerative building goal. The technical solutions are collected in an open-source database that is available from the COST Restore website and is freely accessible to the academic and professional community. A specific framework has been developed, in order to facilitate the identification of connections between technologies, environmental aspects and sub-aspects, and the functional solutions that enable the achievement of the regenerative goals. The solutions have been analyzed focusing on the three main sub-systems of the building (building envelope, interior elements and finishes, and active systems). About 50 technical solutions were collected from the participants of WG4, from the trainees of the 4th Restore training school, and from the case studies of regenerative buildings collected in the WG4. The solutions that have mainly been considered are applicable to office buildings. As said, the aim was to create an open platform in which scientists and practitioners are fully able to operate, giving their inputs and finding suitable solutions for a diverse set of design options. An overview of how the database can be used to select solution-sets for regenerative building design has been described in section 7.4, which includes an example of the works of the trainees from the 4th Restore training school.

As explained in the previous paragraphs, most of the technologies that have been collected are capable of controlling the hygro-thermal environment, in which indoor comfort is by far, the most widely studied aspect of regenerative building. Similarly, indoor air quality and acoustic environments also appear to be well represented as environmental aspects that can be managed with advanced technical solutions. The number of technical solutions with capabilities to control the visual environment are in lower number, while only a few technical solutions are capable of controlling human values. It has to be highlighted that the showcase collection of technical solutions was selected, with a view to an even distribution of technologies within the three sub-systems. Therefore, some aspects are still missing, although technologies that can manipulate them still exist. The collection of these technologies should be a priority for the future expansion of the database. For this reason, the database cannot be considered as exhaustive, but merely an example of how technologies can be collected.

Finally, as explained beforehand, further work is still needed, and the database will be continuously updated with new technologies and solutions. Some priorities are mentioned below:

- Seek solutions capable of manipulating under-represented aspects. As an example, some of the passive techniques to control both visual and acoustic environments have a limited number of solutions in the database.
- Consider solutions for interior finishes and active systems capable of improving human values within the building.
- Integrate multi-functional solutions that are capable of impacting upon and controlling more than one environmental aspect at the same time. According to the survey results, a good number of solutions (about 40% of the total) only showed benefits for one environmental aspect and less than 15% of the collected solutions only showed benefits for all the environmental aspects that were considered.

The last point highlights how work is still needed from the professional, industrial and scientific communities to achieve the goal of an integrated and holistic approach, which is the basis of the restorative approach. Finally, the aim is to populate the database with information on technologies that will also prove suitable for other building typologies (such as, for example, residential buildings, educational buildings, hospitals), which were not analyzed in the first instance.

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7 THE ENVIRONMENTAL AND SOCIAL IMPACTS OF REGENERATIVE TECHNOLOGIES AND THEIR EVALUATION

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CONTENT

7.1 FROM A THREE-DIMENSIONAL APPROACH TO A COMPREHENSIVE VISION FOR AN INTEGRATED SUSTAINABLE DESIGN

In a fast urbanizing world, the development of our cities and towns, so that they may be of greater sustainability, and even fully regenerative, is an extremely valuable endeavour. While many technological solutions increase the energy and material efficiencies of cities, the pace of their development may not, it has been suggested, be sufficiently rapid to turn the tide against the increasing consumption of assets and services that lead to greenhouse gas emissions, resource consumption, and environmental degradation, in general. In this chapter, we will explore how a holistic vision of the environmental, social and economic aspects of a building may be designed to go beyond "doing less bad" to "doing more good" for the environment. The broad topic is the transition from current to low-impact and to achieve regenerative cities and other human settlements and buildings. "Regenerative" refers here to actions, policies and technologies that have a net-positive impact on the environment.

The most recent approach to sustainability is therefore the regenerative approach, built upon regeneration of the system, so that it remains healthy and so that damage is independently prevented [Sonetti et al., 2018, 2019] . The aim is not just to limit or to repair the damage, but to create long-life healthy systems, based on a harmonious relationship between humans and nature. Moving human behaviour towards their surroundings from an ego-centric dominant position over nature to eco-friendly actions towards nature, and finally to the SEVA "social and economic value-added" approach to nature.

With the ascent of the Agenda 2030 as a combining framework for sustainability, the building sector has been struggling towards the complete inclusion of its goals and targets. Grounded upon the review of the recent literature, existing trials and attempts at integration have focused attention on environmental assessment criteria rather than on the possible interactions between buildings and the SDGs. The integrated design process, which has been commonly used in sustainable building projects, is seen as the most suitable setting for beginning to think of both the environmental and the social impacts of regenerative technologies in a new way and their evaluation.

According to the "Roadmap to a Resource Efficient Europe," (RREM, 2011) [European Commission, 2011) better construction and use of buildings could help towards essential resource savings: it could influence 42% of final energy consumption, around 35% of total GHG emissions, 50% of extracted materials, and it could save up to 30% of water in some regions. Moreover, we spend over 90% of our time within buildings, which means that the regenerative indoor environment is a massive and highly influential part of any proposed solution. Accomplishing a regenerative indoor environment requires a set of innovative methods for rethinking the technologies that are used starting from the design phase.

So far, there is no one recognized description or definition of a sustainable building. However, several guiding principles and standards have been established to assess (and to verify) how buildings achieve specific environmental and ecological standards.

Kibert [Kibert, 2008] proposed the following description of green buildings: "healthy facilities designed and built in a resource-efficient manner, using ecologically-based principles". A description that is mostly focused on the ecological effects of the construction, omitting the way that the building can influence and interrelate with its surroundings and its occupants.

RICS [RICS, 2009] described sustainable buildings as follows: "Sustainable buildings should optimize value for their landlords and inhabitants and the wider public, while minimizing the usage of natural resources and giving low environmental influence, including their influence on biodiversity." This description has a broader scope, as it includes end-user perceptions and the interaction of the construction with its surroundings. The previous definition is consistent with Berardi [Berardi, 2013], who claimed that a green building should not only be in tune with the environmental characteristics, but should likewise be "designed and operated to match the suitable fitness for the use with the least environmental influence."

Cole [Cole, 2010] argued in favour of a difference between green and sustainable building assessments: a green building assessment should emphasize the local environmental characteristics, with conventional building, applied as a point of departure, though a sustainable building should be evaluated by using pre-defined international sustainable (economic, environmental, and social) goals. However, others have argued that any definition of the overall sustainability standards is impossible in relation to the overall built environment, as it is especially context-dependent [Cooper, 1999], [Goodland and Daly, 1996], [Pearce, 2006] and [Williams and Millington, 2004]. Terms such as "green" or "sustainable" are frequently used to indicate that construction is built in harmony with a third-party environmental assessment system [Zalejska-Jonsson, 2013].

The Building Research Establishment's Environmental Assessment Method (BREEAM) was the first green building rating system in the UK that addressed the required Key Performance Indicators (KPIs) for better environmental performance of buildings. In 2000, the U.S. Green Building Council (USGBC) developed another rating system, which is the Leadership in Energy and Environmental Design (LEED). Others also responded to the growing interest and demand for sustainable design including additional rating systems, most of which were influenced by these early programmes, but are tailored to their own context with specific priorities. Other rating-system pathways have sought to address broader issues of sustainability and evolving concepts such as social aspects, net zero energy, and living and restorative building concepts. It is estimated that there are nearly 600 green product certifications in the World with nearly 100 in use in the USA, and the numbers continue to grow.

The literature on those approaches focuses more on overall schemes for building sustainability assessment rather than a list of individual indicators. At the same time, the literature has mainly been focused on assessing the environmental impact of buildings using LCA assessment methods and tools. The integration of LCA assessment methods in the early stages of design saw Building Information Modeling (BIM) as the umbrella for integrating environmental impact awareness in a standardized design and as a visualization tool for the construction industry sector.

With the advent of sustainable material selection and sustainable housing, numerous resources and tools have been created to aid informed decisions.

Contemporary technologies, such as BIM, and energy modelling have shed an innovative light on the way architects and engineers reflect upon the methods with which buildings are designed and built. New approaches, such as energy performance modelling have transformed the techniques that designers use when planning buildings. This change in the progressive design processes has meant that constructions are additionally efficient, as it means that designers can make an additional comprehensive long-term assessment of the buildings they are planning [O'Connor and Bowrick, 2014]. Alternatively, evolving technology in this field has meant that designers can inspect the embodied effects of the building design, expanding the understanding of the environmental impacts of buildings.

7.2 LIFE CYCLE THINKING (LCT) AND GREEN BUILDING RATING SYSTEMS

LCA is a system that can be used to measure the whole life cycle of a product or process, including pre-production, production, and implementation, in which environmental characteristics are mainly considered. Economic and social characteristics are measured by applying Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA), as additional methods with which to measure the economic and social features of a process or product life cycle. The considered LCA measures a portion of the environmental impacts of building materials. For decision-makers, it is necessary to be familiar with all aspects of the environmental impacts of a product or process.

The National Risk Management Research Laboratory (NRMRL), part of the United States Environmental Protection Agency (EPA), describes life cycle assessment as "a cradle-to-grave approach for measuring industrial systems that assesses all phases of a product life cycle. It delivers a comprehensive view of the environmental characteristics of the product or process" [Curran, 2006].

Although a mature concept, LCA is gaining ground, because it can be used to quantify the environmental impacts of design choices that span the entire life of the project. In the past, LCA was used to compare products and building sets, which provided some indication of how to progress with decision making, but provided no data on the long-term impacts resulting from construction operations.

There is also a wide-ranging life cycle thinking method which fairly considers all the environmental, economic, and social topics that is known as Life Cycle Sustainability Assessment (LCSA]. The LCSA is formally expressed with the following equation [Kloepffer, 2008]; [Finkbeiner et al., 2010]:

$$LCSA = LCA + S\text{-}LCA + LCC$$

while LCA, S-LCA, and LCC can each be independently used. The formal equation means that the three methodologies must be implemented simultaneously and with equivalent system boundaries [Finkbeiner et al. 2010]. Clarification and translation of the results of the social impact for a product or a process into numerical values is not a simple job. Therefore, agreement on this subject is hard to fulfil, and the proposed solutions are often inadequate [Whitehead et al., 2015].

Whole Building Life Cycle Assessment (WBLCA) has proven to be a complex exercise practiced by experts [Giesekam, Barrett, and Taylor, 2016]. Even though it has been incorporated into Green Building Rating Systems (GBRS), it is only in recent years that standardized methodologies have become accessible for building designers. The available methodologies are diverse and use a variety of international standards as their primary references. These variations imply differences in goals and scope, particularly in relation to the description of the functional or reference units and system boundaries.

The varied approaches to WBLCA that are available in different GBRS for the evaluation of embodied carbon are a barrier for precise comparisons between buildings assessed with different tools, and likewise for the development of baselines to drive estimated reductions of environmental impact [O'Connor, 2017]. A standardized WBLCA methodology must be established for the building industry using simplified tools, in order to continue making advances with the holistic environmental assessment in buildings, including more robust databases and a large body of knowledge.

A Life Cycle Assessment (LCA) tool is used by industry professionals to select environmentally preferable products, assemblies, or entire functional areas, with a reference service life of 60 years. Typically, only one method of analysis or tool may be utilized for a given building project. The results of an LCA are reported in terms of the environmental impacts listed in this practice and state whether operating energy was included in the LCA [ASHRAE-b, 2016]. In recent years, simplified LCA methods have been developed for industry practitioners (i.e., Tally plug-in for REVIT).

A recent review by Soust-Verdage et al. [2017] indicates that the BIM approach and tools for organizing building information are currently being used to estimate environmental and energy consumption impacts based on LCA, using templates and plug-ins for BIM software and automated processes for combining different data and software [Soust-Verdaguer, Llatas, and García-Martínez, 2017].

BIM can help simplify the estimation of carbon emissions over a building's life cycle, because it provides most of the information and calculation tools necessary for performing a Life Cycle Assessment (LCA), which may lessen the problem of insufficient information when performing an LCA of a building [Peng, 2016]. BIM-enabled environmental impact feedback processes can assist designers making decisions with significant impact during the early design stages, while deferring decisions with a marginal impact until later design stages [Basbagill, Flager, Lepech, and Fischer, 2013].

WBLCA showed promise for evaluating and motivating lower impact buildings; however, better LCA data – i.e., guidelines for conducting whole building LCAs and databases with a large number of reference buildings – will be needed, in order for accurate assessment of the actual improvements that can be applied to a specific building [Simonen, 2014]. Previous reviews have looked at WBLCA case studies of residential and non-residential buildings and the tools used to carry out the assessment [Cabeza, Rincón, Vilariño, Pérez, and Castell, 2014] [Ortiz, Castells, and Sonnemann, 2009]. Reviews have also found gaps regarding environmental indicators, easily understandable LCA results presentations to users, and the adaptation of LCA for various purposes [Zabalza Bribián, Aranda Usón, and Scarpellini, 2009].

In 2014, the European Commission launched an initiative for the creation of a common European approach towards efforts to organize the sustainability assessment of buildings [EU, 2014]. It then developed Level(s), in 2017, a voluntary framework for a sustainability report of buildings, to unify the efforts working towards the sustainability assessment of buildings and to create a common "sustainability language," Level(s) consists of a series of indicators that are designed to assess sustainability at different levels of complexity, thereby unifying the units that quantify indicators, laying the groundwork for comparisons between projects, and optimizing the sustainability of the building [Dodd, Cordella, Traverso, and Donatello, 2017]. The framework, in which more than 130 buildings in 21 countries are being assessed, is still in the test phase and its official launch is planned for the summer of 2020 [EU, 2014].

Even though the aforementioned sustainability rating systems have Environmental Life Cycle Assessment (E-LCA), which is equivalent to LCA, as part of their assessment, the approaches and assumptions made in each case can vary significantly from one to the other, which could lead to discrepancies in the results.

LCA is still considered the best practical approach to perform an environmental impact analysis of a product [Coma, Pérez, and Cabeza, 2018], system and organization. LCA is a scientific, standardized method regulated by the International Standards ISO 14040-14044:2006. It is a tool of proven validity for environmental impacts assessment of construction materials and buildings. Moreover, it allows the consideration of all inputs and outputs related to the product or building throughout its whole life cycle. Even though it is a standardized tool, LCA allows some flexibility in terms of choosing the scope of the assessment, and the environmental impacts for assessment, among other aspects. With LCA, the assessment of all kinds of products and services with different characteristics is possible. Concerning the construction industry, an LCA can be done at two levels: product level and building level. At the product level, Environmental Product Declarations (EPD) is a verified and transparent way to communicate product-specific environmental data, obtained from an LCA. These data sources are preferred when performing an LCA of buildings, as the environmental information refers to specific products from specific manufacturers, which ensure precise LCA results.

EPDs are preferred as a data source to perform an LCA on most of the Green Building and Product Rating Systems (GBPRS), as they provide specific data.

7.3 LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA) PRACTICE

The design process should be based on a comprehensive approach that includes all life cycles and that captures a complete sustainability assessment, supporting the transition towards regenerative design. An appropriate approach is the Life Cycle Sustainability Assessment (LCSA).
Efforts have likewise been made to include economic aspects and social issues in life cycle analysis, in order to arrive at a complete sustainability assessment [Kloepffer, 2008].
Kloepffer and Matthias defined LCSA, with the previously mentioned formal equation: LCSA = LCA + LCC + S-LCA [Kloepffer 2008] [Finkbeiner et al., 2010].
Nowadays, no general standard is available for social and economic dimensions, due to the complex nature of assessing both economic and social issues.
Over the course of time, LCC has been standardized in the building sector with the International standard ISO 15686-5, which specifies a standard definition of LCC and the steps for its application to a building. The interest in standardizing this methodology had previously arisen, in 2006, when Davis Langdon Management Consulting, under contract to the European Commission, developed a standard European methodology for Life Cycle Costing (LCC) in construction with additional details, in order to specify how LCC could be integrated into European policymaking. By 2007, the use of LCC for measuring the economic value of the retrofitting action was proposed: e.g., retrofitting for earthquake protection and the best mechanism for doing so [Chang, Wilkinson, and Mellahi, 2007]. LCC is also included in a few certification schemes such as: “Deutsche Gesellschaft für Nachhaltiges Bauen” (DGNB) [German Sustainable Building Council], both for the assessment and for the certification of the sustainability performance of a building.
The LCC is not a focus of this chapter, but many case studies and examples of its implementation can be found in the literature. To summarize the concept, an LCC mainly consists of the inventory of all costs and revenues incurred in a product life cycle. It can be used for raw materials, components, and the entire building. In the case of the entire building, the use phase plays an important role, and the life span of a building is established as 60 years, so that it is comparable with the results of LCC in the building. The first software has now been developed, LEGEP© https://legep.de/produkte/legep-lebenszykluskosten/, a tool for integrated life cycle analysis that supports planning teams with the design, construction, quantity surveying and assessment of new and existing buildings and building products. The LEGEP database contains the description of all elements of a building (DIN 276); and their life cycle costs (LCC/WLC) (DIN 18960).
No standards are at present available for social LCA, although the first guidelines were already published in 2009 by the UNEP Life Cycle Initiative [UNEP, 2009; Benoit Norris et al., 2009]. A revision was necessary, because lots of improvements and developments have taken place over those last ten years, and it once again became one of the activities of the UNEP LCI, in 2018.
The LCSA and S-LCA have not as yet been widely implemented in the building sectors, and neither have they been applied for retrofitting work on buildings. We will therefore not present an example of the regenerative technology, but a more general description of the methodology will be given, as well as references on its application within the building sector.
The general LCSA framework is comprehensively described in a publication from UNEP, where all phases are explained, including both reporting and case studies for the comprehensive method [Valdivia, et al., 2013]. The case study reported in the UNEP [2011] is a complete LCSA on a marble slab. It was a project completed with primary data on the three dimensions collected from two central Italian Marble Basins: Custonaci (in Sicily) and Massa e Carrara (Tuscany). Even if this case study was performed some years ago, there are not many other implementations in the building sector. The most common studies are on the assessment of the environmental dimension, even if the title of the study often reports the sustainability assessment method. In the other available studies, the LCA and LCC have mainly been integrated with a socio assessment that is not in line with the S-LCA definition. Finally, the last group of studies on this topic has had a sharper focus on the interpretation phase of the LCSA results, such as Traverso et al. [Traverso, M. et al., 2012] and Junjua et al. [Janjua et al., 2019].
We will now provide a general introduction to S-LCA, and its current state of the art, while underlining both the challenges and the benefits to its implementation in the building sector. Then, a description of the steps necessary to implement the LCSA will be given, to support interested LCA users when applying LCSA.

7.3.1 SOCIAL LCA

The Social Life Cycle Assessment (S-LCA) was defined for the first time several years ago, and the definition of O'Brian M, Doig A, and Clift R [1996] was among the first definitions, in 1996 [Kloepffer, 2008]. Other essential milestones to define S-LCA for a product and as the third pillar of LCSA are the publications of Klöpffer and Matthias [Finkbeiner et al., 2010]. In those publications, the S-LCA is defined as a complementary approach of LCA and LCC to assess the social impacts of a product throughout its life cycle. As also reported in the publication from UNEP [Ciroth, A. et al., 2011], the same functional unit, and an equivalent system boundary should be considered in that approach.
The first milestone of the S-LCA methodology was in the form of the UNEP guidelines for the Social Life Cycle Assessment of Products, published in 2009 [Benoît-Norris et al., 2010]. It introduced the LCA methodology for users and experts and gave an overview of its historical background. Developed as a complementary approach to the previously standardized environmental LCA, S-LCA followed the same framework as the ISO 14040 [ISO, 2006]: goal and scope, life cycle inventory, life cycle impact assessment, interpretation. However, the two methodologies had several differences in their theoretical and practical implementation; the main steps in the S-LCA are as follows:

- Definition of stakeholder categories, the results of S-LCA depend on the stakeholder category chosen.
- Assessment of positive and negative impacts
- Strongly dependent on the Impacts of the local conditions and company behaviour, rather than on the production process.
- Definition of the variability activities
- The necessity to start with a social hotspot assessment

Table 23. Stakeholder categories and impact subcategories according to the UNEP 2009.

"Workers"	**"Consumer"**
1. Freedom of Association & Collective Bargaining	1. Health & Safety
2. Child labour	2. Feedback Mechanism
3. Fair Salary	3. Consumer Privacy
4. Working Hours	4. Transparency
5. Forced Labour	5. End-of-Life responsibility
6. Equal opportunities/Discrimination	
7. Health and Safety	
8. Social Benefits/Social Security	
"Local community."	**"Society"**
1. Access to material resources	1. Public commitments to sustainability issues
2. Access to immaterial resources	2. Contribution to economic development
3. Delocalization and Migration	3. Prevention & mitigation of armed conflicts
4. Cultural Heritage	4. Technology development
5. Safe & healthy living conditions	5. Corruption Value chain actors (not including consumers)
6. Respect for indigenous rights	6. Fair competition
7. Community engagement	7. Promoting social responsibility
8. Local employment	8. Supplier relationships
9. Secure living conditions	9. Respect for intellectual property rights

According to the current literature, two primary references are now available: the previously mentioned guidelines for Social Life Cycle Assessment of products [UNEP, 2009; Benoît-Norris et al., 2009] and the Handbook for Product Social Impact Assessment (PSIA) [Fontes et al, 2016] [Fontes et al., 2018]. Both approaches described in the two references are quite similar and consistent with each other, and both consider among the stakeholder categories (or Groups): workers, local communities, and users/consumers. The two guidelines refer to users/consumers in different ways, although they play the same role. An overview of the stakeholder categories and impact subcategories according to UNEP 2009, is given in Table 23.
The Handbook for Product Social Impact Assessment (PSIA) was developed and published by the Roundtable of Product Social Metrics. The main goal of this initiative was the development of a qualitative and quantitative methodology for the social impact assessment of products. Starting with the scientific references already available, a certain number of topics were selected. Those topics were then matched against the company strategies and priorities. This approach led to the identification of a certain number of issues, called impact categories and related indicators. In the PSIA Handbook, the indicators that should be considered for each impact category are defined and, in Version 3, a quantitative and qualitative approach is reported to assess the social impact of a product.
For the assessment, both the UNEP 2009 and the Handbook for PSIA [Fontes, 2016; Fontes et al., 2018; Traverso et al, 2018] guidelines were used, as well as a life cycle inventory for both qualitative and quantitative assessment. A compendium document, called the Methodological Sheets, was necessary, because the UNEP guidelines were considered very technical, which was published in 2013 [Benoît-Norris et al., 2013]. These Methodological Sheets present each impact subcategories and describe them in detail giving: definitions, political context, the relation with sustainable development, and generic and specific data sources. A list of subcategories considered in the UNEP guidelines and the Methodological Sheets are reported in Table 23.
In the Handbook for PSIA, consideration was given to three of the five stakeholder categories (called the group in the Handbook): workers, local communities, users, and in the small-scale entrepreneurs that were added to the 2018 Version of the Handbook. Those categories and the relevant impact categories are listed in Table 24.

Table 24. Stakeholders categories from the Handbook for PSIA.

"Workers"	**"Local communities."**
1. Health and Safety	1. Health and Safety
2. Remuneration	2. Access to tangible resources
3. Child Labour	3. Community engagement
4. Forced Labour	4. Employment
5. Discrimination	
6. Freedom of Association & Collective Bargaining	
7. Work-life balance	
"Users"	**"Small-scale entrepreneurs"**
1. Health	1. Meeting basic needs
2. Product safety	2. Access to services and inputs
3. Responsible communication Privacy	3. Women's empowerment
4. Inclusiveness	4. Child Labour
5. Effectiveness and comfort	5. Health and Safety
	6. Land rights
	7. Trading relationships

As we can see, by comparing Table 23 and Table 24 for workers and the local community, several topics in both documents are the same or at least equivalent. The similarities are shown in bold text in Figure 39.

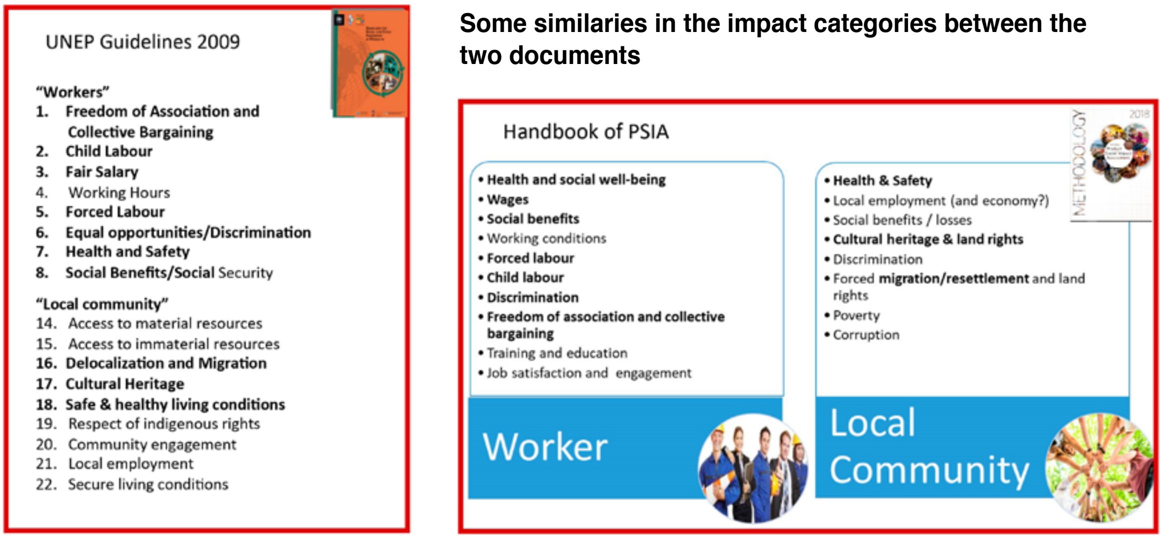

Figure 39. A comparison between the impact categories considered in the UNEP guidelines and the handbook for PSIA.

The use phase is, in general, the least explored and assessed in the S-LCA; most implementations are mainly performed to assess the impact on workers throughout the supply chain and product life cycle and in the local communities. The use phase in the case of the building could play an important role, if we consider that a typical building will be in use over an extended time span (100, 60, 50 years); those periods will depend on the calculation assumption and will meaningfully affect the overall social impact. Moreover, the use phase can be very complicated, because lots of the stakeholders are involved, such as maintenance workers, workers in the supply chain of the materials used in maintenance, users of the building, owners of the building, and the local community where the building is sited. Hence the need for a first screening, to understand which the main stakeholder categories actually are.

UNEP published "The methodological sheets for sub-categories in Social Life Cycle Assessment (S-LCA)" in 2013 [Benoît-Norris, et al. 2019], to give additional support to the implementation of S-LCA in a more practical way. It is a compendium document to the UNEP Guidelines that provides a better explanation of the impact subcategories, references for a hotspot analysis, and indicators at generic and specific levels. Those two levels of analysis, generic and specific, are fundamental, because they introduce the difference between the assessment of a social risk at country and sector level according to the general database (generic level) and product assessment, in which primary data are considered from the company in situ. It also has a stakeholder questionnaire (specific). Databases at a generic level are available today such as Social Hotspot Database (SHDB) [Benoit-Norris, Cavan, and Norris, 2010] and A Product Social Impact Life Cycle Assessment (PSILCA) database. Sectors are available in both databases on minerals and raw materials for construction.

With the generic data, a more social Hotspot analysis is possible, to identify which main issues should be considered. A life cycle inventory would need a questionnaire, to have a more specific assessment and eventually to measure the positive social impact caused by the product. A positive social impact can occur, because the social performance of the product and the unit processes can be improved when the practice of the company is improved in comparison with the local social conditions.

After the collection of inventory data, an assessment of the impact according to reference values (type 1) or throughout social impact pathways (type II) is necessary.

The referencing principal is used today. It can be obtained starting from either a qualitative inventory analysis or the collection of quantitative data. Lastly, in both cases, those values will be compared with a reference value, in order to obtain a score according to the concept that refers to the target.

The SAM methodology and its indicators and subcategories refer to the UNEP guidelines and the methodological sheets. According to SAM, it is possible to compare the LCI data with the minimum requirement for each impact category, in accordance with to the International Labour Organization conventions and other international agreements. Four levels are introduced by SAM: A, B, C, D, and each of them as a score from 4 to 1. As shown in Figure 40, if the company owner of the life cycle steps considered in the assessment is compliant with the minimum requirement, then its rating will be B; if it is proactively improving its social performance and following best practice in that area, then its rating will be A. C and D both mean non-compliant, but they depend on the local conditions. If the local conditions are critical for that specific aspect, then non-compliance is critical, which means it is rated as D, or otherwise C.

Level	Criteria
A	The organization shows proactive behavior by promoting best practice and is a front runner.
B	The organization meets the basic requirements and national laws and international conventions relating to each aspect.
C	The organization fails to meet the basic requirement and is in a local context with a high social risk.
D	The organization fails to meet the basic requirement and is in a local context with a very high social risk.

Figure 40. Evaluation ranking for Subcategory Assessment Method (Sanches et al.2014).

A similar approach is followed by the PSIA method. PSIA evaluation is based on 5 categories, see Table 25, and, in this case, we have a reference level, which is an indicator as 0, and it is obtained when the data show compliance with local laws or with international standards. If there are some conflicts between national and international norms, then international standards are preferred. According to the PSIA, we have two levels of positive impact and two levels of negative impacts, differentiated according to the definition shown in Table 25.

Table 25. Evaluation criteria, according to PSIA. Source: Fontes [2016].

2	Ideal performance; a positive output achieved and reported
1	Progress beyond compliance is made and monitored
0	Compliance with local laws and aligned with international standards
-1	The non-compliant situation, but actions to improve have been taken
-2	No data, or Non-compliant situation; no action has been taken

Today the implementation of S-LCA to an entire building is quite complicated, because no database for components and materials is as yet available. As mentioned, a social hotspot analysis is possible, which the existing database can support.

7.3.2 SOCIAL LCA FOR THE BUILDING SECTOR

Particular attention should be given to the materials and components supply chain when assessing building scenarios and future regenerative technologies. Hence the need for an inventory of material that should be carried out as the first step. For each of the materials and components, the supply chain should be identified, including companies involved and the location of the production, manufacturing, and processing plants. With the data on the location, a social Hotspot analysis could be developed by using either SHDB or PSILCA: in both cases, the main stakeholder categories and subcategories can be identified. To do so, a questionnaire should be developed to collect primary data from the company and plants involved. A consequent analysis of the results, according to SAM or PSIA, may be then carried out. In the data collection phase, particular attention should be given to the identification of stakeholders and local NGOs that are well integrated in the local context and that can validate the inventory data.

The process can be summarized in the following steps:
1. Describe the material life cycle, including extraction of raw materials, manufacturing, and logistics.
2. Identify the main stakeholder categories.
3. Identify their main production places (if the specific production and extraction sites are not available).
4. Proceed with a Hotspot analysis, using the Social Hotspot Database and PSILCA.
5. Develop a specific questionnaire on the impact of subcategories and stakeholder categories that are identified as part of the Hotspot Analysis.
6. Collect qualitative data by using the PSIA approach or quantitative data by using SAM methods.
7. Calculate the impact and interpret the results accordingly.

For the building sector, the use phase represents a challenge that is usually neglected in the current S-LCA studies. The use or operational phase in building plays an important role, and involves several stakeholder groups. Considering a building life span of about 60 years, examples of stakeholder categories are users, facility managers, workers in the supply chain of materials, and components necessary to maintain the building. In terms of social impact for users, which are undoubtedly the most affected stakeholders, comfort, and health impact categories should be considered. No impact categories have been developed yet in the current S-LCA methodology, but often the comfort or indoor air quality have been considered in other fields and sometimes in the LCA. Further research is necessary here for greater consistency in the methodology.

The implementation of LCSA follows the ISO 14040 framework: goal and scope, life cycle inventory, life cycle impact assessment, and interpretation.

Even if the general steps are the same, the first difference will be in the definition of goals and scope, where the main stakeholder groups (or categories according to the S-LCA), an equivalent system boundary, and the functional unit must be defined. The stakeholder categories are chosen to take into account those that play a meaningful role in accounting for social and economic aspects. In fact, for both pillars, the definition of stakeholder categories/groups is necessary, in order to define which data and indicators should be considered in the assessment:
1. LCC -all money flows are different, if the company producer or the customer, etcetera. is considered as a stakeholder
2. S-LCA – different impact subcategories and different indicators will be selected according to the chosen stakeholder categories. Health and Safety can be measured differently, if it refers to local communities or workers or even to consumers.

The definition of the system boundary also considers the three pillars that are the reason why it consists of all process units which have at least one relevant impact in one of the three pillars. Then last, but not least, the functional unit should be defined, considering its functionality in society and at the economic level. It is particularly important when one or more products are compared with each other. This scenario is clearly explained in the UNEP 2011 publication [UNEP, 2011] in the case study of the marble slab.

The life cycle inventory and calculation of impact assessment have been done up until today in parallel on the three dimensions, taking care to avoid double counting. As in the case of health impacts on workers and/or local communities caused by emissions, those impacts are included under the social rather than the environmental impacts. In LCC, it is essential to consider the real cash flow and not to monetize the social and environmental externalities, if those externalities generate no real cash flows.

7.4 TOWARD A COMPREHENSIVE ASSESSMENT OF THE SUSTAINABILITY DIMENSION

The aim of sustainable development is to improve and to increase the quality of life for all on a planet that is finite in its physical resources and its capacity to absorb waste. As defined by the Brundtland Commission report [WCED, 1987], the term implies that a balance can be achieved between human socio-economic activities and the capacity of the natural environment to provide resources and absorb waste on a global scale. Recent research has, however, indicated that our global demand began to outstrip the carrying capacity of the planet in the 1980s [Wackernagel *et al*, 2002]. Today the ecological footprint of the world population/economy exceeds the total productive area (or ecological space) available on a planet [Rees & Wackernagel, 1996]. Today the ecological footprint of the world population/economy exceeds the total productive area (or ecological space) available on a planet [Rees, Grubb and Kelly, (1996)]. Extreme environmental, economic, and social impacts of climate change are exponentially emerging when compared to the efforts invested in mitigation and adaptation. This impact has proven that sustainability, which mostly focuses on limiting the damage, might not be insufficient in itself. It has required experts to adopt new approaches, and the second step is the restorative approach, which still mainly emphasizes repairing the damage that has been caused.

The regenerative approach is built upon the principle of helping the system to remain healthy, so that it can independently prevent the damage. The aim is not merely to limit or to repair the damage, but to create long-life healthy systems based on a harmonious relationship between humans and nature. A comprehensive assessment of a regenerative dimension of key urban planning issues and building design strategies should look at the following issues.

1. Human Impact (including quality of life issues, consultation and social inclusion, development factors, comfort levels, health factors, accessibility, public transportation, facilities for cyclists, etc.).
2. Environmental Impact (including protection of local ecological features/biodiversity, environmental assessment, etc.).
3. Pollution Prevention (including indoor air quality -emissions from equipment, out-gassing of toxins/radiations- elimination of toxins, control of pollutants during constructions, etc.).
4. Sustainability Management (including integrated and systemic approaches e.g., sustainability/environmental performance targets, management systems and procedures, construction management, commissioning, dissemination workshops, post-occupancy feedback visits, etc.).
5. Resource Efficiency (including, lean design, material use and recycling, embodied energy, water consumption and conservation, etc.).
6. Energy Efficiency (including, targets, benchmarks and best practice energy use, passive solar, renewable energy, thermal modelling, insulation, ventilation, heating, CHP, heat recovery, etc.).

The above themes are aligned with aspects of the ISO 14001 international standard and offer a basis for the development of a sustainable buildings management system. It implies the identification a number of tasks that need to be undertaken, relating to the design, the construction and the operation of sustainable environments. In line with the description of sustainable building from the UK Government Department of Environment, Food and Rural Affairs (DEFRA), a sustainable design strategy for urban development should:

- fit well with the needs of the local community;
- leave as small an environmental footprint as possible;
- be economically viable throughout its whole life cycle;
- be designed and constructed to enable occupants to use less water, for example, through the installation of more efficient fittings and appliances;
- provide good access to public transport;
- minimize waste in construction;
- maximize the re-use of on-site materials such as waste soil;
- be energy and carbon efficient, and be designed to minimize energy consumption, with effective insulation and the most efficient heating or cooling systems and appliances;
- and, make recycling easy for the occupants.

Environmental Life Cycle Assessment (E-LCA) has developed fast over the last three decades. Today, E-LCA is widely applied and used as a tool for supporting policies and performance-based regulation, nota-

bly concerning bioenergy. Over the past decade, LCA has broadened and now includes Life Cycle Costing (LCC) and social LCA (SLCA), drawing on the three-pillar or 'triple bottom line' model of sustainability. With these developments, LCA has broadened from merely environmental assessment to a more comprehensive Life Cycle Sustainability Assessment (LCSA). LCSA has received increasing attention over the past years, while at the same time, its meaning and contents are not always sufficiently clear.
Following the Guinée *et al.* [Guinée et al., 2011] definition of LCSA, we see the following challenges as crucial to address first (one challenge for each dimension of LCSA):

1. Broadening of impacts: proper, preferably quantitative and practical indicators for SLCA.
2. Broadening the level of analysis: develop, implement and apply life cycle-based approaches to evaluate scenarios for sustainable futures.
3. Deepening: develop and implement ways to deal with uncertainties and rebound effects as comprehensively and practically as possible.

The challenge to develop proper, preferably quantitative and practical indicators for SLCA has been present ever since SLCA was proposed as a possible approach.
Another challenge is the interpretation of the results. According to the current state of the art of the LCSA, there are around 31 social indicators (according to the current, and not the revised, version of the 2009 UNEP guidelines); two economic indicators (costs and revenues) considering only the perspective of the company owning the building; and, 17 environmental midpoint indicators (for example in the Product Environmental Footprint (PEF)). A significant number of indicators that needs to be interpreted and combined in a more integrated value.
No agreement has yet been reached as to the road forward, in this case, examples of tool and methodologies available today are: Life Cycle Sustainability Dashboard [Traverso et al., 2012]which assesses product performance considering the environmental, economic, and social dimensions of the life cycle. The results of LCSA can be used to compare different products or to support decision making toward sustainable production and consumption. In both cases, LCSA results could be too disaggregated and consequently too difficult to understand and interpret by decision makers. As non-experts are usually the target audience of experts and scientists, and are also involved in decision-making processes, the necessity for a straightforward but comprehensive presentation of LCSA results is becoming strategically important. The implementation of the dashboard of sustainability proposed in this article offers a possible solution. An outstanding characteristic of the dashboard of sustainability is the communicability of the results by means of a graphical representation (a cartogram, Multi-Criteria Analysis [Hannouf and Assefa 2018], and The Life Cycle Sustainability Triangle [Finkbeiner et al. 2010].
Considering the period over which discussions around the challenges of SLCA have continued, one may wonder 'whether it is really appropriate to model social LCA on environmental LCA'; and, whether or not 'Social LCA is more likely to develop as a useful tool, if it is not forced into the mound of environmental LCA' [Clift, 2014]. This discussion is not new, since Udo de Haes [see Klöpffer, 2018] had previously argued, in 2008, that 'social indicators do not fit in the structure of LCA', because developing 'a quantitative relationship of the indicator to the functional unit' or properly handling the high spatial dependency of the indicator is problematic when trying to squeeze such impacts into environmental LCA. To prevent progress on SLCA coming to a dead end, a fundamental re-examination of the SLCA paradigm appears necessary, eventually leading to increased applicability and to a more comprehensive coverage of social benefits and life cycle impacts.
All our life cycle tools should be accompanied with proper approaches to data uncertainty, methodological choices, assumptions and scenarios and preferably also with proper ways of handling rebound effects. This aspect is particularly important, as the results of our tools are increasingly supporting public policies and performance-based regulations. However, most of our studies still present their results as point values, suggesting that life cycle tools produce black and white results with no uncertainties, while all experienced practitioners of these tools know otherwise. Thus, in order to maintain and increase the credibility of our life cycle decision-support tools, we need to develop approaches, as a priority matter, to respond to the uncertainties associated with data, models, choices and the assumptions of all life cycle-based methods (LCA, LCC, SLCA, IOA, hybrid LCA, etc.) in a proper and transparent manner.

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8 VISION FOR THE FUTURE

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Nature-built environment-humans are all part of the same system (SEVA vision, compared to EGO and ECO, as reported in the RESTORE WG1 booklet) and the key for defining optimal interactions can be nothing less than an interdisciplinary approach that includes building physics, cognitive science, sociology, medicine, environmental science, and economics. Such an interdisciplinary approach will help find well-balanced solution-sets for technologies that, properly applied, will serve to define regenerative indoor environments. Regenerative environments that will both restore and improve the natural environment (and humans likewise), perfectly integrated within a built environment (building and surroundings), by enhancing the quality of life for both biotic (living) and abiotic (chemical) elements.

Building smartness increases awareness and the transformation of collected data into useful information can support further investments to transform existing building stocks.

While the textbook definition of the regenerative indoor environment is defined in terms of IEQ and human values, there are also some technical aspects to be considered such as statics, fire safety engineering, and architectural quality, which can affect both building durability and resilience.

Local microclimatic and contextual dynamics affect building performance, while either directly or indirectly affecting environmental and social impacts throughout the life cycle (e.g. high financial add-ons, as regenerative building can even have negative social impacts, because of tax increases to finance the building itself). Over the next few years, such a comprehensive evaluation, involving different themes and performed throughout the life cycle, will become even more important and will, in building design, normally include procurement, construction, commissioning, and O&M up to the end-of-cycle. The above-mentioned comprehensive evaluation will need an implementation strategy, based on physical indicators and related calculation methods.

Clear quantitative and objective calculations of the co-benefits that are contributing to real estate value are of primary importance. From that point, there is still the need to (naturally) motivate behavioural change, by providing training, information and gamification building management to raise awareness.

Thinking of a paradigmatic shift in the approach to building design, it is also important to introduce stochastic analysis, in order to define life cycle variable boundary conditions in the design phase, thereby ensuring durability and avoiding obsolescence.

The best introduction of advanced technologies for regenerative indoor environments will need a deep integration of building value chain players, ensuring a continuous commitment throughout the whole process: concept-design-implementation-commissioning-O&M-end of cycle (at the natural end of the life cycle or when the boundary conditions change).

There is still a need to define a standardized set of KPIs as a common language for construction industry players that can be used to describe a regenerative indoor environment, to enable an extensive consensus of the stakeholders on the market and a collective effort in the same direction to enhance the quality of the built environment.

The built environment can be characterized as the embodiment of human values and ingenuity, as represented by the knowledge and priorities of its creators. Further, the acquisition and assimilation of the knowledge to create the built environment are clearly shaped by a broad range of contextual issues [Cole and Lorch, 2003]. It means that a regenerative indoor environment may have different nuances depending on both the social and the cultural context, which is something to be further investigated and structured within a specific knowledge framework. Technology solutions related to envelope, interior finishing, technical systems, RES harvesting and control, can contribute to achieve a regenerative indoor environment and their effects must be evaluated through measurement and verification, including standardized approaches for post occupancy evaluation and for the availability of open-source databases containing raw survey data. There is no absolute optimal set of solutions for a regenerative indoor environment, but a repository of such solutions that will also highlight the connections between KPIs and functions that can effectively support both the design and the implementation phases, by providing good examples within specific contexts.

Finally, the impact of a regenerative technology must be evaluated from a life cycle perspective, promoting such an approach for supporting the decision-making process, as is already done in ICT service. Life Cycle Sustainable Assessment must include environmental, economic and social aspects as formalized in the following equation:

$$LCSA=LCA+LCC+S\text{-}LCA$$

Regenerative building can provide specific and collective value for the efforts of all stakeholders, positively balancing benefits and impacts, but they need a comprehensive decision-making process that can clearly define performance targets and functions (e.g. including fire safety issues when evaluating BIPV and greenery integration within the building envelope).

Lack of knowledge and awareness among construction industry players on what can actually contribute to a regenerative building still appears as a central issue, the solution to which could be support through a specific legislative framework enabling a meaningful market uptake where customer choices are mainly driven by initial investment. Integrated business models, connecting design-building-management and taking into account human value can drive the building stock transformation in a regenerative direction. There is a need for effective and affordable tools for implementing such a transformation, to support designers when promoting novel technologies, including information sharing systems, such as Building Information Modelling (BIM) and related data handling such as building energy modelling, monitoring in building operational phase, and big data analytics. There is a need for effective and affordable tools for implementing such a transformation, to support designers when promoting novel technologies, including information sharing systems, such as Building Information Modeling (BIM) and related data handling such as building energy modelling, monitoring in the building operational phase, and big data analytics.

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The Working Group 4 of the COST action “RESTORE” worked towards proper characterization and identification of the technologies and the solution-sets for a regenerative indoor environment. This booklet, the fourth published within the project, represents the natural continuation and the progressive development of the concepts reported in the respective booklets of the first three Working Groups.

Proper technology solution-sets can enable a regenerative indoor environment for building users and for the planet, thereby ensuring the wellbeing and the health of building occupants and citizens alike. Several aspects are considered for high indoor environmental quality, such as hygro-thermal comfort, visual comfort, indoor soundscape, indoor air quality, and a pleasant ambiance. Regenerative indoor environmental quality must be achieved, through the minimization of environmental and social impacts linked to the solutions, while making optimal use of resources throughout the entire set of life cycles.

Key technologies can promote a paradigmatic shift in building design from “less bad” to “more regenerative”. However, proper technologies need a dedicated evaluation framework for aware selection within a comprehensive decision-making process. Nature-built environment-humans are part of the same system (SEVA vision, compared to EGO and ECO, as reported in the RESTORE WG1 booklet) and an interdisciplinary approach covering building physics, cognitive science, sociology, medicine, environmental science, and economics is the key for defining these optimal interactions. Such an interdisciplinary approach will help design well-balanced solution-sets for technologies that, properly applied, will serve to define regenerative indoor environments.

These guidelines are intended for practitioners and can be used to approach aware design and assessment of indoor regenerative environments with examples of solution-sets within the building domain and case studies.

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