Solution-sets for a regenerative environment

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Regenerative technologies for the indoor environment

Inspirational guidelines for practitioners

EDITORS
Roberto Lollini, Wilmer Pasut

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6 SOLUTION-SETS FOR A REGENERATIVE ENVIRONMENT

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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]

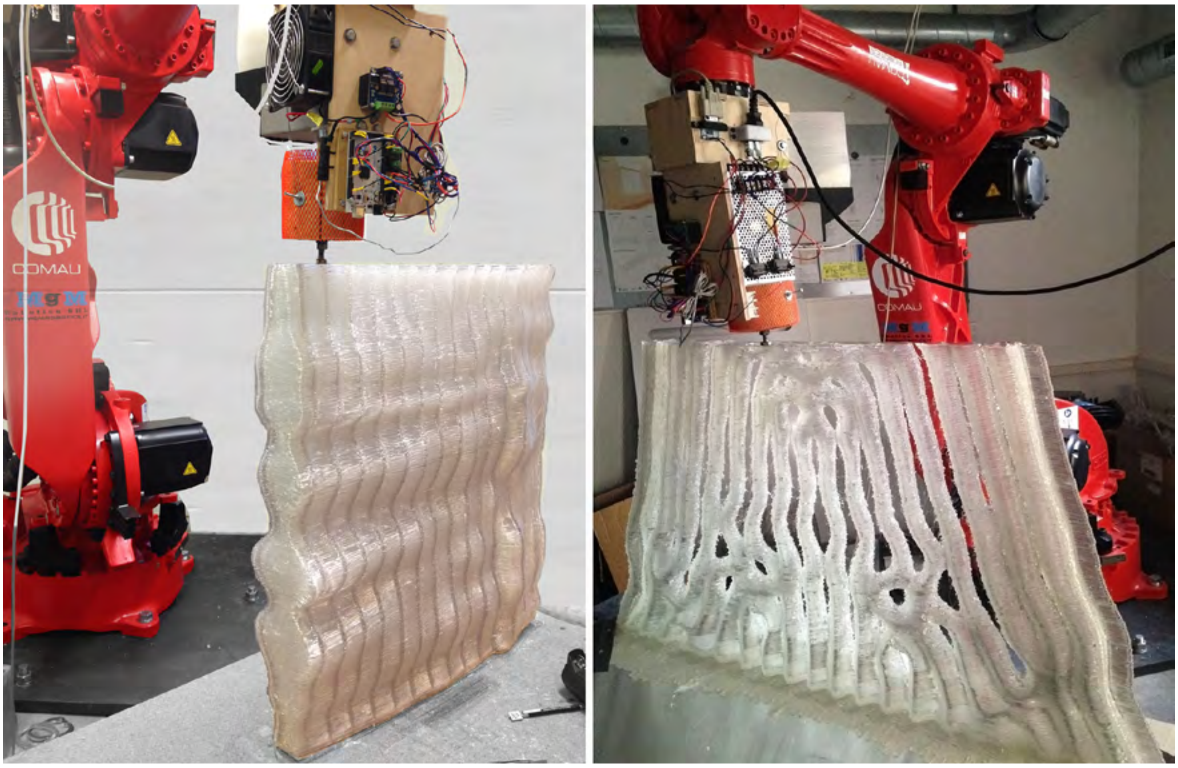

Figure 31. Robotic FDM 3D printing of the Double face 2.0 prototype [source: Tenpierik et al., 2018*].*

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 perfor-mance 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 trans-mission 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 certifi-cation			X	X						X	X		X		
Antibacterial TiO2 coating and Respon-sive 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 CO2 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., CO2, 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 photo-catalytic 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).

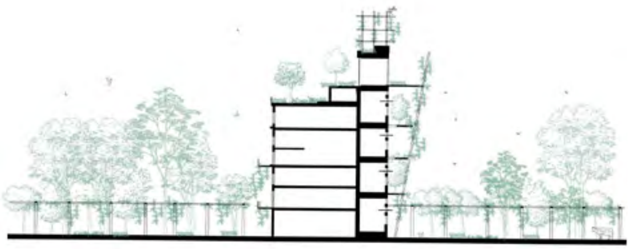


Figure 34. Section and impression of the building, showing the double skin façade addition and the introduction of natural elements.

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.

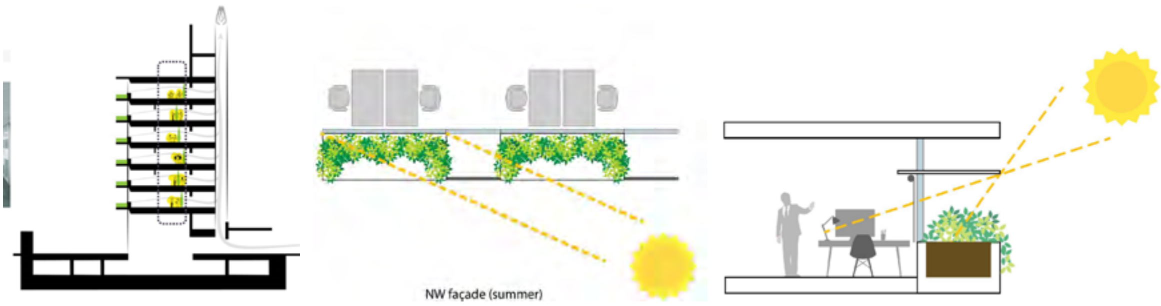

Figure 35. The double facade acts as a solar chimney to enhance air movement and has balconies redesigned with green walls and shading elements.

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.

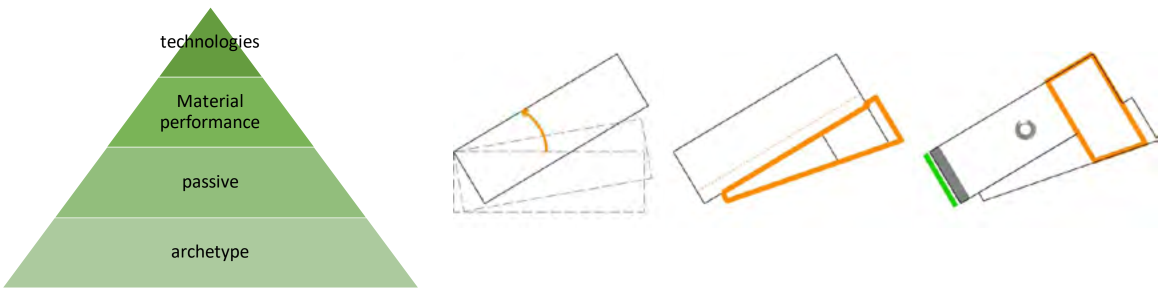

Figure 37. The holistic approach to regenerative indoor environment includes architectural and geometrical characteristics, passive design principles, such as the construction of a thermal buffer, and material performance, such as recyclable materials.

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.

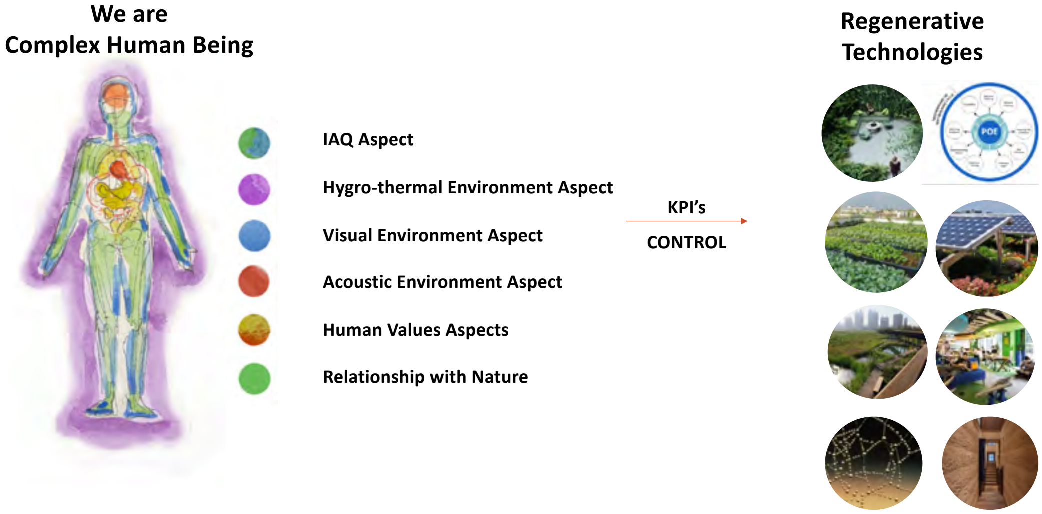

Figure 38. The steps that the regenerative technological solutions follow, starting from the premise that a person is a complex individual, and moving to the evaluation of user needs in compliance with environmental aspects and KPIs. The combination of all these aspects led us to the definition of the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