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OFFICE: Occupant-tailored Facility Fostering Innovation
in Controlling Energy-efficiency

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Abstract

OFFICE is an Occupant-tailored Facility Fostering Innovation in Controlling Energy-efficiency, which is planned to be realized within a multi-disciplinary research framework – launched by Politecnico di Torino – having the aim of fostering local development in the energy field by means of collaboration between university, industry, and policy makers: Energy Center Initiative (ECI).

It is by now ascertained at international level that smartness is the future of cities, and thus of buildings. The implementation of smart solutions will enhance the sustainability of the built environment operation in terms of energy efficiency and benefits to the citizens. OFFICE will be a tool for studies on smart energy management in office environments, with particular focus on the present situation at local level, and on the role of the occupants. The facility will be set up as an office environment where occupants work under test scenarios varying in the way services – such as heating, cooling, ventilation, lighting, etc. – are provided, and in the Human-Building Interaction modes offered. The tests goal is supporting local energy planning in the definition of cost-effective strategies by means of scientific research and technological application.

The aim of this dissertation is identifying the design requirements of the facility and proposing solutions in terms of space layout and envelope, so as to provide insights before the actual design takes place. The project background – set up for this kick-off study, but suitable for the sake of future developments – consists in: the analysis of the international energy policy context; the review of worldwide existing facilities for energy- and occupant-related studies; the individuation of the test objectives according to the research framework of Energy Center Initiative.

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Glossary

Building Automation and Control (BAC). Products, software, and engineering services for automatic controls, monitoring and optimization, human intervention, and management to achieve energy-efficient, economical, and safe operation of building services equipment.
EN 15232-1:2017 (E); EN ISO 52000-1:2017

Building Automation and Control System (BACS). System comprising all products, software and engineering services that can support energy efficient, economical and safe operation of technical building systems through automatic controls and by facilitating the manual management of those technical building systems.
Directive (EU) 2018/844

System, comprising all products, software and engineering services for automatic controls (including interlocks), monitoring, optimization, for operation, human intervention, and management to achieve energy-efficient, economical, and safe operation, human intervention and management to achieve energy-efficient, economical, and safe operation of building services. BACS is also referred to as BMS (Building Management System).
EN 15232-1:2017 (E); EN ISO 16484-2:2004

Building Management (BM). Totality of services involved in the management operation and monitoring of building (including plants and installations).
CEN/TS 15379:2006

Constant Air Volume (CAV) Ventilation. System supplying a constant airflow at variable temperature. CAV systems are well-suited for applications where the ventilation load is constant for large periods of time. The only viable control method is to operate fans intermittently with ON-OFF switches, but this is not energy efficient and causes uncomfortable temperature variations. In addition, CAV systems in general have poor humidity control.
https://www.ny-engineers.com/blog/ventilation-system-comparison-cav-and-vav [Acc. 01/12/18]

Displacement Ventilation. Air distribution technology that introduces cool air into a zone at low velocity, usually also at a low level. Buoyancy forces ensure that this supply air pools near the floor level, allowing it to be carried up into the thermal plumes that are formed by heat sources.
https://www.priceindustries.com/content/uploads/assets/literature/engineering-guides/displacement-ventilation-engineering-guide.pdf [Acc. 26/03/18]

Energy Efficiency. Ratio or other quantitative relationship between an output of performance, service, goods or energy, and an input of energy. Both input and output need to be clearly specified in quantity and quality and be measurable.
EN 15232-1:2017 (E); EN ISO 50001-1:2011

Energy Need for Heating of Cooling. Heat to be delivered to or extracted from thermally conditioned space to maintain the intended space temperature conditions during a given period of time.
EN 15232-1:2017 (E)

Human-Building Interaction (HBI). The study of the interface between the occupants and the building's physical space and the objects within it. HBI focuses on system interactions and interconnections with the aim of lowering the building-occupant system's energy use
Shen (2015), p.6.

Integrated Building Automation and Control Systems. BACS designed to be interoperable and with the ability to be connected to one or more specified 3rd party building automation and control devices/systems through open data communication network or interfaces performed by standardized methods, special services and permitted responsibilities for system integration.
EN 15232-1:2017 (E)

Mixed Flow ventilation. The traditional method of supplying air to ventilated spaces. Cool air is blown in through the ceiling or wall and dilutes the room air to provide an even temperature and contaminant level through the space. With mixed flow ventilation the flow is driven by the inertia of the supply air.
http://www.ambthair.com/displacement_vs_mixed_flow_ventilation.html [Acc. 26/03/18]

Operative temperature (t_{op}). Uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment.
ISO 7730:2005 (E)

Readiness. Capability of a technology, a system or a building to implement smart functions and services. For instance, a system can be smart-ready (e.g. a controllable heat pump) but not smart (the controllable heat pump is not connected to a controller and / or has no configuration interface).
Verbeke et al. (2018), p.197

Set-point temperature of a conditioned zone. Internal (minimum) temperature, as fixed by the control system in normal heating mode, or internal (maximum) temperature, as fixed by the control system in normal cooling mode.
EN 15232-1:2017 (E)

Smart Ready Service (SRS). Service enabled by (a combination of) Smart Ready Technologies defined in a technology neutral way. The term "ready" indicates that the option to take action exists, but is not necessarily realized, e.g. due to cost constraints, legal or market restrictions, or occupant preferences. However, the equipment needed to implement the service has to be present in the building.
Verbeke et al. (2018), p.32

Smart Ready Technologies (SRT). Technologies which can be either digital ICT technology (e.g. communication protocols or optimization algorithms) or physical products (e.g. ventilation system with CO_2 sensor, cabling for bus systems) or combinations thereof (e.g. smart thermostats).

Such components could potentially:

- raise energy efficiency and comfort by increasing the level of controllability of the TBS – either by the occupant or a building manager or via a fully automated building control system;
- facilitate the energy management and maintenance of the building including via automated fault detection;
- automate the reporting of the energy performance of buildings and their TBS (automated and real time inspections);
- use advanced methods such as data analytics, self-learning control systems and model predictive control to optimise building operations;
- enable buildings including their TBS, appliances, storage systems and energy generators, to become active operators in a demand response setting.

Verbeke et al. (2018), p.32

Smartness. The ability of a building or its systems to sense, interpret, communicate and actively respond in an efficient manner to changing conditions in relation the operation of technical building systems or the external environment (including energy grids) and to demands from building occupants.

Verbeke et al. (2018), p.32

Technical Building Management (TBM). Process(es) and services related to operation and management of buildings and technical building system through the interrelationships between the different disciplines and trades.

EN 15232-1:2017 (E)

Technical Building System (TBS). Technical equipment for space heating, space cooling, ventilation, domestic hot water, built-in lighting, building automation and control, on-site electricity generation or a combination thereof, including those systems using energy from renewable sources, of a building or building unit.

Directive (EU) 2018/844

Thermally Activated Building System (TABS). Combined heating and cooling system with pipes embedded in the structural concrete slabs or walls of multi storey buildings.

Babiak J., Vagiannis G. (September 2015) Thermally Activated Building System (TABS): Efficient cooling and heating of commercial buildings, Conference paper, Conference: Climamed 2015, Juan-Les-Pins, France.

Massive building fabric actively heate or cooled by integrated air or water based systems.

EN 15232-1:2017 (E)

Under Floor Air Distribution (UFAD). Method of delivering space conditioning used in offices and other commercial buildings as an alternative to conventional ceiling-based

air distribution systems. This technology uses the open space (underfloor plenum) between the structural concrete slab and the underside of a raised access floor system to deliver conditioned air directly into the occupied zone of the building. Improved thermal comfort, improved indoor air quality, and reduced energy use are some of the advantages of UFAD systems over traditional overhead systems.
https://www.cbe.berkeley.edu/underfloorair/techoverview.htm [Acc. 02/12/18]

Variable Air Volume (VAV) Ventilation. System supplying a variable airflow at constant temperature. VAV systems offer superior performance in any application where ventilation equipment is subject to frequent part-load conditions. In addition to energy efficiency, a VAV system provides superior control over temperature and humidity. Equipment also lasts longer because it is not subject to frequent switching, like equipment using ON-OFF controls in CAV ventilation systems.
https://www.ny-engineers.com/blog/ventilation-system-comparison-cav-and-vav [Acc. 01/12/18]

Acronyms index

AHU	*Air Handling Unit*
BAC	*Building Automation and Control*
BM	*Building Management*
DHW	*Domestic Hot Water*
DSF	*Double Skin Façade*
ECI	*Energy Center Initiative*
EPB	*Energy Performance of Buildings*
EPBD	*Energy Performance of Buildings Directive*
EV	*Electric Vehicle*
HBI	*Human-Building Interaction*
HVAC	*Heating, Ventilation and Air Conditioning*
IAQ	*Indoor Air Quality*
ICT	*Information and Communication Technologies*
RH	*Relative Humidity*
SRI	*Smart Readiness Indicator (for Buildings)*
SRS	*Smart Ready Service/Services*
SRT	*Smart Ready Technology/Technologies*
TBM	*Technical Building Management*
TBS	*Technical Building Systems*

The future of energy in the built environment envisages the increase of efficiency by means of smart technologies. Smart buildings are also expected to improve the occupants' experience by offering favourable human-building interaction strategies. In a transition panorama, with many outdated buildings, and occupants used to deal with that, which is the cost-optimal way to keep up with present needs? Which is the trade-off between Smart Building and a smart occupant behavior?

1. Introduction

The subjects addressed in this dissertation concern a research framework envisaging the collaboration between industry, university, and policy makers: Energy Center Initiative (ECI). Launched in 2016 by Politecnico di Torino, ECI aims at promoting and implementing ventures for supporting the definition of energy policies at local, national, and international level, with reference to the background of European energy policy drivers, such as regulation and guidelines. As set out in the document stating its mission, Energy Center's goal is combining the creation of a network at national and European level, the promotion of entrepreneurship in the energy field, and the generation of knowledge and innovation in the sector. The combination of these activities may raise from the synergy and information exchange between the actors playing a role in Energy Center facilities, which are: Politecnico di Torino, Public Administration (i.e. Città Metropolitana di Torino, Regione Piemonte), and companies in the first place, but also private research institutions, energy corporations, grid operators, and financial entities. To sum up, Energy Center mission is creating a multi-disciplinary research hub fostering local development in the energy field, with reference to the national and international panorama, through the synergy between scientific and technological knowledge. Within Energy Center Initiative, Energy Center Lab (EC_lab) is the Interdepartmental Center where multi-disciplinary research is carried out and studies on present and future scenarios of energy management are performed, focusing on environmental, economic and social sustainability. The physical location of EC_lab is EC_house, a high energy performance building in Politecnico campus, aimed at work and research (offices, laboratories, meeting rooms and an auditorium are housed there) where any enterprise or institution can find room for operating activities consistent with EC mission.

FIG.1. EC_house hall. Source: Energy Center – Politecnico di Torino http://www.energycenter.polito.it/

The first case study tackled by the new-born EC_lab will involve the local entity at city level, Città Metropolitana di Torino, with the aim of planning and shaping a smart city in terms of smart energy management in buildings and mobility, considering the integrated management of local energy grids and the maximization of local energy production from renewable sources.

The project described in this dissertation, concerns the definition of the requirements and some design features of OFFICE, an Occupant-tailored Facility Fostering Innovation in Controlling Energy-efficiency. It is meant to be a facility where tests supporting EC_lab research are carried out. Its purpose, for which facility requirements and design indications are provided in this dissertation, is hosting experiments about the overall energy performance of an office environment, by means of efficient technical building systems management and smart technologies employment, with attention to the occupants' comfort and well-being. Such experiments will firstly be applied to the case study of Città Metropolitana di Torino and dealing with energy management in office environments located in existing or even outdated buildings. The aim of the studies performed in OFFICE laboratory is devising cost-effective strategies for enhancing the energy performance and sustainability of office buildings in Torino, through the integration of innovative technologies and smart systems, thus reaching an equilibrium between smart building and smart occupant behavior. With reference to the mission of Energy Center Initiative, OFFICE investigations will envisage the cooperation of university, public administration, and enterprise for obtaining various effects: first, carrying on local research in the fields of Energy Performance of Buildings and Human-Building Interaction; second, providing insights to the municipality for local energy planning; and third, allowing smart technology producers to promote and test their products in a realistic environment.

Following the multi-disciplinarity characterizing EC_lab ventures, OFFICE project envisages the collaboration between different fields of expertise. The present dissertation aims at defining the requirements of OFFICE facility and at pointing out the central features of its design – in terms of spatial organization and envelope – in order to lay the foundations for subsequent developments and the eventual realization of the laboratory. For the sake of project completeness and because of the mentioned multi-disciplinar approach, other subjects must be addressed, yet not being included in this argumentation. They consist in the planning and dimensioning of the technical building systems, and the identification of ICT solutions to be employed in the facility.

The facility shall be set up as an office environment where occupants work under test scenarios varying in the offered Human-Building Interaction modes, spanning from manual to automated control conditions. The scenarios – and therefore the strategies and technologies implemented in them – will be evaluated according to the energy savings they can produce, but also according to occupant comfort and positive attitude towards the interaction with the building. The final goal of OFFICE tests is finding answers to the following question, whose relevance is recognized at international level (Wagner and O'Brien, 2018): which is the trade-off between building automation and smart occupant behavior, providing optimal results in both energy efficiency and occupant satisfaction?

The structure of this dissertation follows the path leading to the requirements identification and features definition of the facility. The local actors involved in OFFICE activities – namely Politecnico di Torino, local administration, and companies operating in the energy field – play a role within a broader panorama of energy transition, whose direction is outlined at European level through guidelines and regulation. Chapter 2 offers an overview on European perspective with respect to energy efficiency in the built environment. Besides the policy context, reference to existing facilities of different typology, but sharing some common ground with OFFICE, needs to be made. Chapter 3 analyzes a set of existing laboratories and present research in the fields of indoor climate, energy performance of buildings, occupant behavior, Human-Building Interaction, building automation, etc. Chapter 4 analyzes in depth the test objectives and defines the strategies for meeting them, while Chapter 5 clarifies the facility requirements and the spatial constraints according to which design solutions are proposed: it displays design solutions in terms of articulation of the space, architectural technologies, materials, test tools. Finally, Chapter 6 addresses future developments of OFFICE.

2. European strategies for energy efficiency and smartness in the built environment

In the last two decades the European Union has been taking on different measures to tackle the energy consumption matters that are now interesting the whole planet. In 2002 the Directive 2002/91/EC on the energy performance of buildings stated that “Energy consumption for building-related services accounts for approximately one third of total EU energy consumption”. The document underlines the potential of new buildings (and existing ones going through major renovation) in terms of enhanced energy performance. In more recent years the problem of energy consumption and energy inefficiency in the building sector showed to be still current, also more and more urgent. In 2010 the European Commission focused on providing broader indications on the energy performance of buildings by means of Directive 2010/31/EU. A few years later the document is amended through Directive (EU) 2018/844, where the successfulness of energy efficiency strategies in the built environment is described as strongly dependent on the smartness of the buildings and more broadly on the smart management at city level. A smart city, where information is collected, developed, and shared in real-time among smart buildings, vehicles, devices, etc. allows smarter distribution and use of available energy. Hence, a transition towards smarter cities must be fostered through dedicated policies and regulatory updates.

When it comes up to the single building, the employment of the smartness as an evaluating criterion is not yet a present practice. The European Union refers to the smartness of a building in terms of smart readiness, which means quantifying the capability of the building, with reference to its characteristics and those of its technical building systems, to adopt Smart Ready Technologies (SRT) and Smart Ready Services (SRS). For this reason, Directive (EU) 2018/844 recommends the creation of a Smart Readiness Indicator, in order to quantify and compare the smart readiness of buildings, thus approaching the actors involved in buildings use and management to the notion of smartness in the built environment, encouraging the inclusion of the latter among real estate valuation criteria, and supporting the adoption of smart technologies. A European multi-expertise consortium (VITO, Energy Ville, ECOFYS, Waide Strategic Efficiency, OFFIS) including expertise in the fields of information and communication technologies (ICT), building physics, economic and environmental assessment, and market and consumer analysis, is indeed carrying on a project for providing technical support to the Directorate-General for Energy of the European Commission in setting up the Smart Readiness Indicator for buildings. One of the main results of the study, which is presented in the final report about the first phase of the project, is the methodology definition for assessing the smart readiness of a building, considering the services it offers and the functionality of those services, in relation to different impact criteria.

The regulatory aspect of the smartness in buildings and their energy performance is deeply referred to in standard EN 15232 (2017), that is part of the Energy Performance of Buildings (EPB) set of standards and deals with automation and systems control in buildings. The standard focuses on Building Automation and Control and Technical Building Management topics and shows in detail how to measure the automation level of technical systems in buildings, therefore also determining the related energy efficiency level.

The aspects of the documents and research mentioned above, constituting interesting material for the aim of this study, are treated in more detail in the following paragraphs. In particular: 1.1 deals with European Directives on the Energy Performance of Buildings; 1.2 addresses the multi-expertise project on the Smart Readiness Indicator for buildings definition; and 1.3 describes European standard EN 15232 (2107).

To sum up, since a few decades Europe is facing the global matter of energy consumption, where the great use of energy in the built environment must be tackled with the evolution of the energy management system at city level. This means finding out the most efficient balance in distributing energy from various sources to buildings with diverse functions and to different transportations; it means moving steps towards the grid flexibility by means of technologies employment and users' education. The required energy efficiency can indeed be reached through the employment of Smart Ready Technologies (SRT) and Smart Ready Services (SRS), enabling an optimized and flexible use of energy, according to the needs of the grid, of the occupants, and of the environment. Within the transition panorama towards a smart city paradigm, the project presented in this dissertation fits in the process of generation of smart buildings, a challenging operation which will require some time for reaching its full completion, and must be faced finding out, step by step, the most cost-effective strategies. Established that the energy performance of buildings, besides depending on the use of efficient technical building systems and high performing architectural technologies, can be enhanced by automated control, we can assume that the currently most widespread human-building interaction approach – relying on occupant-controlled solutions, often lacking the opportunity of fine tuning and subject to unaware handling – needs to be reversed. In the perspective of an increasing uptake of building automation, building occupants will stop being the main actors of technical building systems control; however, they might be provided with more information for becoming energy-aware, and thus willing to accept a lower level of control.

2.1. Directive 2010/31/EU and Directive (EU) 2018/844

The directive presented in this paragraph belong to the EPBD (Energy Performance of Buildings Directives). Directive 2010/31/EU provides indications on the energy performance of buildings; the requirements for new and existing building are identified and particular focus is addressed to boosting the realization of nearly zero-energy buildings, whose definition is provided by the directive itself. Other expressions related to the energy performance of buildings and on the operations to enhance it are defined: major renovation, energy performance certificate, cost-optimal level, to name a few. The directive underlines the importance of considering and accommodating local circumstances; in fact, it aims at promoting "the improvement of the energy performance of buildings within the Union, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness". Moreover, it underlines that public authorities and public buildings should set an example of good practice in terms of energy efficiency.

This document is amended in 2018 by Directive (EU) 2018/844, with the aim of strengthening certain aspects of the provision and simplifying others. Once again, the importance of reducing greenhouse gas emissions is highlighted, and in particular European Union commits to reduce them further by at least 40% by 2030. Being the building stock responsible for about 36% of CO_2 emissions in the Union, solutions for decarbonizing energy supplies and reducing energy consumption must be sought. Energy efficiency must therefore be considered as a priority when renovating the building stock.

With a view to decarbonizing our cities, smart mobility is one of the fundamental requirements. Innovating the building stock can leverage the deployment of electric vehicles providing the necessary infrastructure for their charging. Besides, a mutual advantage can arise from the relation between buildings and electric vehicles since it is possible to use the batteries of the latter as a power source for buildings when the power supply does not meet the demand. This is indeed a situation which is likely to happen in a scenario where energy is mainly produced from renewable sources, unevenly available by nature.

As well as smart mobility, smart grids and smart-ready buildings take part in the energy management evolution of the near future of our cities. The digitization of the energy system represents an opportunity for energy savings, since it facilitates the monitoring of energy use, the share of information about consumption patterns provided to consumers, and a more effective management of the grid by the system operator. In order to make building owners and occupants aware of automation technologies and their potential, the Union recommends the use of a *Smart Readiness Indicator* (referred to as SRI), measuring the capacity of the building of adapting its operation to the occupants' and the grid needs. In Directive 2018/844 the definition of the *Technical Building Systems* is indeed updated in view to the smart-ready building, including the systems of building automation and control, and on-site electricity generation.

The aim for which the project presented in this dissertation will be initially employed, is understanding which level of smartness would best suit an office environment for meeting the energy efficiency targets and providing occupants' comfort, while being cost-effective. This program comes in a transitional situation, where most existing office buildings present situations of excessive energy waste and need to increase their smartness. Being the test facility limited at one single room, experiments will focus on indoor environmental conditions and Human-Building Interaction in a smart-ready office. Aspects concerning the energy management at a larger scale, such as electric mobility, local power production and storage will be set aside: experiments concerning these matters would indeed better fit a test facility consisting in an entire building.

2.2. European project for supporting the definition of a Smart Readiness Indicator for buildings

Following the indications of the amended EPBD, a multi-expertise consortium (VITO, Energy Ville, ECOFYS, Waide Strategic Efficiency, OFFIS) was created to provide technical support to the Directorate-General for Energy of the European Commission in setting up a *Smart Readiness Indicator for Buildings*. The project, started in 2017, is expected to be concluded by July 2020, when a final report on the indicator will be delivered. Within the project duration, several phases and activities are planned with the aim of collecting material to fuel the discussion on the topic at European level. The first phase was concluded in 2018 and a report delivered (Verbeke et al., 2018). In this document, the Smartness of a building is defined as "the ability of a building or its systems to sense, interpret, communicate and actively respond in an efficient manner to changing conditions in relation to the operation of Technical Building Systems or the external environment (including energy grids) and to demands from building occupants". In short, a smart building is able to combine information from different backgrounds (i.e. environment and occupants) and sort the most efficient response for the Technical Building Systems operation. The smartness of a building relies on ICT-based solutions acting on energy efficiency and energy management flexibility for reducing energy footprint and carbon impact of the building itself, and for creating a healthy, comfortable, safe and secure environment for the occupants, and beneficial for the activities they perform in it.

The SRI should become an instrument to provide a common language for different stakeholders, and to encourage the uptake of Smart Ready Technologies. As declared in Directive (EU) 2018/844, SRI is a voluntary scheme for rating the smart readiness of buildings – thus attributing a consistent and tangible value to the benefits provided by smart technologies – aimed at different stakeholders. Building owners, tenants and occupants will get information about the services the building can deliver, potential improvements, favourable investment opportunities; smart service providers will benefit of a standard rating system through which services and products can be compared with the competitors. The various actors involved in buildings use and management reflect indeed different aspects of smart readiness of buildings, such as adapting to the occupants' needs, facilitating maintenance and efficient operation, adapting to the energy grid situation.

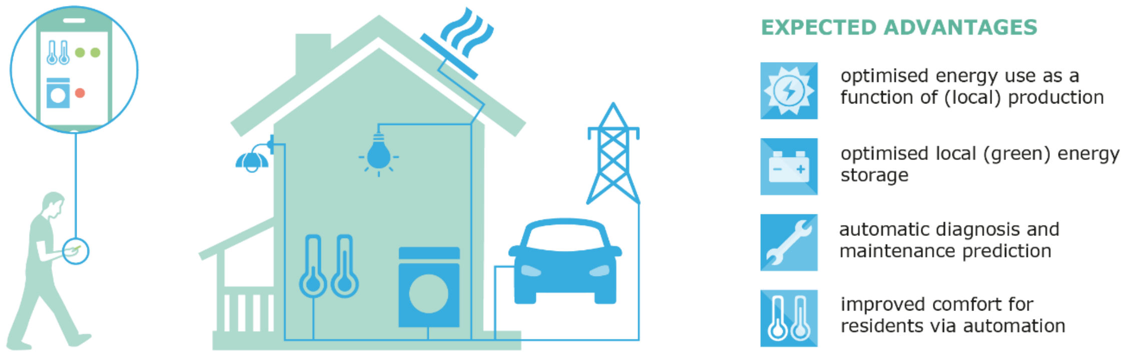

FIG.2. Expected advantages of Smart Ready Technologies employment in buildings. Source: Verbeke et al. (2018), p.7.

According to the study, the SRI assessment consists in an inventory of the Smart Ready Services present in a building and the functionality levels (or degree of smartness) they offer. While defining the Smart Ready Services three key functionalities have been taken into account:

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

The services are clustered into ten domains, the higher the smartness of the services, the higher the impact on the building and its occupants.

Heating. Services for enhancing operations of the heating system, i.e. storage, generation, distribution and emission of heat.
Cooling. Services dealing with thermal storage, emission control systems, generators and energy consumption for space cooling.
Domestic hot water. Services for smarter control of generating, storing and distributing DHW.
Controlled ventilation. Services for air flow and indoor temperature control important drivers for both energy demand in a building, and occupants' health and comfort.

Lighting. Services for electric lighting control by a system based on different drivers, e.g. time, daylight, and occupancy.

Dynamic building envelope. Services dealing with the control of “passive” building features, i.e. openings and sun shading systems, allowing the reduction of heating/cooling needs.

On-site renewable energy generation. Services for monitoring, forecasting and optimizing the operation of on-site power generation and controlling the storage of energy or its delivery to the connected grid.

Demand side management. Services aimed at managing energy flexibility, that is controlling the demand for energy in response to the current situation of the grid.

Electric vehicle charging. Service of recharge the building provides to the electric vehicles (EV); the benefit of those services can be mutual, since EV might be used as power storage facilitating energy flexibility.

Monitoring and control. Services focusing on sensor data used for optimizing the building and TBS management and operation.

Eight criteria for assessing the impact of Smart Ready Technologies and Smart Ready Services are individuated: *Energy savings on site*, *Flexibility for grid and storage*, S*elf-generation*, C*omfort*, *Convenience*, *Well-being and health*, *Maintenance and fault prediction*, *Detection and diagnosis*, *Information to occupants*. The total score – that is the percentage of how smart ready a building is with respect to the maximum smart readiness it can achieve – is calculated as the weighted sum of those referring to each total impact criterion, the *total impact scores*. Each of those scores is in turn calculated as the weighted sum of ten *domain impact scores*, i.e. percentage values deriving from the combinations of the *impact scores* assigned to each service in the domain, according to its functionality level (**FIG.3**).

The first phase of the project has been developed through the completion of four tasks: Task 1 aims at identifying and characterizing SRT and SRS referring to international standards on energy performance of buildings (EN 15232-1:2017; EN 15193-1:2017) and on software and system engineering (IEC 62559-2:2015); Task 2 deals with the definition of the methodological approach; Task 3 consists in a consultation process of stakeholders and provides a set of updates to the previous two tasks; Task 4 presents an impact assessment of the SRI implementation at European level, intended as benefits and costs analysis or the uptake of SRS.

For the aim of OFFICE project, the most interesting topics are those addressed within Task 1. For instance, the classification of SRS and SRT is a useful tool for choosing which of them should be included in the facility and with which functionality level; the description of the functionality levels and the impact categories boosts considerations about the diverse impacts the smartness of a building might have. Besides describing the SRI methodology, Task 2 provides applications to case study: the one referring to an office environment could provide useful insights for the project of OFFICE Technical Building Systems.

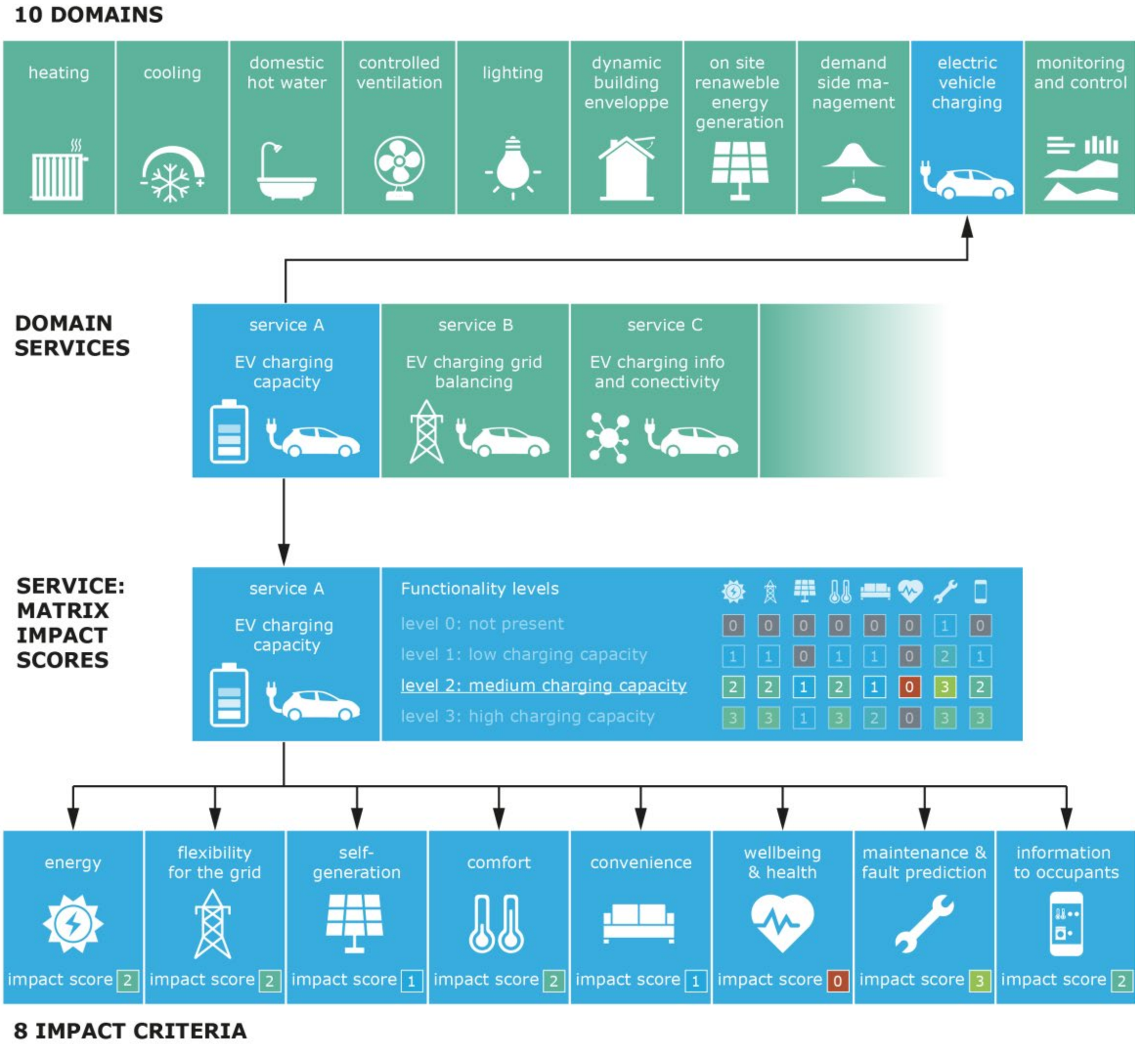

FIG.3. Example of application of the SRI assessment methodology: the functionality level of each SRS individuated, and thus its *impact scores* relating to each impact criterion are expressed. Source: Verbeke et al. (2018), p.23.

2.3. European standard EN 15232-1:2017 (E)

Concerning the regulatory field, standards about Building Automation and Control (BAC), and Technical Building Management (TBM) are defined in EN 15232 of year 2017. The document is included among the set of European standards on the energy performance of buildings (EPB standards), and it presents the BAC and TBM functions contributing to the energy performance of buildings and a method for defining the minimum requirements those functions should respect. Moreover, two methods for calculating the contribution of BAC and TBM functions on the energy performance of buildings are introduced: the *detailed method*, to be used when information about the building, the technical building systems, and the automation type is available; the *factor based* *method*, consisting in a rough calculation made by means of BAC efficiency factors, whose output is the energy demand of a building according to the specific BAC efficiency classification of the building. The document summarizes the most common BAC and TBM functions having an impact on the energy performance of buildings; for each function different automation and control levels are identified. The BAC and TBM functions presented in the standard are listed below.

1. *Heating control*
    - 1.1. *Emission control*
    - 1.2. *Emission control for TABS (heating mode)*
    - 1.3. *Control of distribution network hot water temperature (supply or return)*
    - 1.4. *Control of distribution pumps in networks*
    - 1.5. *Intermittent control of emission and/or distribution*
    - 1.6. *Heat generator control for combustion and district heating*
    - 1.7. *Heat generator control (heat pump)*
    - 1.8. *Heat generator control (outdoor unit)*
    - 1.9. *Sequencing of different heat generators*
    - 1.10. *Control of Thermal Energy Storage (TES) charging*
2. *Domestic hot water supply control*
    - 2.1. *Control of DHW storage charging direct electric heating or integrated electric heat pump*
    - 2.2. *Control of DHW storage charging using hot water generation*
    - 2.3. *Control of DHW storage charging with solar collector and supplementary heat generation*
    - 2.4. *Control of DHW circulation pump*
3. *Cooling control*
    - 3.1. *Emission control*
    - 3.2. *Emission control for TABS (cooling mode)*
    - 3.3. *Control of distribution network chilled water temperature (supply or return)*
    - 3.4. *Control of distribution pumps in hydraulic networks*
    - 3.5. *Intermittent control of emission and/or distribution*
    - 3.6. *Interlock between heating and cooling control of emission and/or distribution*
    - 3.7. *Generator control for cooling*
    - 3.8. *Sequencing of different chillers (generators for chilled water)*
    - 3.9. *Control of Thermal Energy Storage (TES) charging*
4. *Ventilation and air-conditioning control*
    - 4.1. *Supply air flow control at the room level (e.g. fan on/off)*
    - 4.2. *Room air temperature control by the ventilation system (all-air systems; combination with static systems as cooling ceiling, radiators, etc.)*
    - 4.3. *Coordination of room air temperature control by ventilation and by static system*
    - 4.4. *Outside air flow control*
    - 4.5. *Air flow or pressure control at the air handler level*
    - 4.6. *Heat recovery control: icing protection*
    - 4.7. *Heat recovery control: prevention of overheating*

4.8. Free mechanical cooling
4.9. Supply air temperature at the AHU level
4.10. Humidity control

5. *Lighting control*
   5.1. Occupancy control
   5.2. Light level/Daylight control (daylight harvesting)
6. *Blind control*
   6.1. Blind control
7. *Technical home and building management*
   7.1. Setpoint management
   7.2. Runtime management
   7.3. Detecting faults of technical building systems and providing support to the diagnosis of these faults
   7.4. Reporting information regarding energy consumption, indoor conditions
   7.5. Local energy production and renewable energies
   7.6. Heat recovery and heat shifting
   7.7. Smart grid integration

Each BAC and TBM function can assume different states from 0 (representing the absence of automated control) to 3 or 4 (where automation relies on occupancy detection, indoor variables control, etc.). The functions states are related to four BAC efficiency classes – referred to as A, B, C, D class, from the most to the least energy efficient – in order to classify existing and new buildings. This classification is used to investigate both whether the BAC-related energy efficiency level of a building is appropriate, and to define the BAC and TBM functions to be implemented in new construction or renovation operations. The classes mentioned above correspond to the following states.

- A: high energy performance BAC and TBM functions
- B: advanced BAC functions and some TBM ones
- C: standard BAC functions
- D: non-energy efficient BAC

The classification is meant for residential and non-residential buildings. The calculation of the energy performance, both with detailed and factor-based method, should take into account the function of the building, its features and systems: in the first case, only the BAC and TBM functions present in the building must be classified, while in the second case the factor must be chosen according to the function of the building.

2.4. BAC and TBM functions and Smart Ready Services: a comparison

As standard EN 15232-1:2017 (E) is among the sources for SRI project, it is not surprising to notice that seven out of ten domains of services (namely Heating, Domestic hot water, Cooling, Controlled ventilation, Lighting, Dynamic building envelope, Monitoring and control) refer to the BAC and TBM functions categories. However, in each of the seven domains, Verbeke et al. (2018) include some more SRS with respect to the functions in the standard:

- *Heating*: building preheating control; heat system control according to external signal (e.g. energy tariffs); control of on-site waste; report information regarding heating system performance.
- *Domestic hot water*: control of DHW storage temperature; reporting information regarding domestic hot water performance.
- *Cooling*: report information regarding cooling system performance.
- *Controlled ventilation*: reporting information regarding IAQ.
- *Lighting*: mood and time based control of lighting in buildings.
- *Dynamic Building Envelope*: window open/closed control combined with HVAC system; changing window spectral properties.
- *Monitoring and control*: control of thermal exchange; specification that information regarding energy consumption should be current; historical and predicted; services connected to the occupancy detection; spaces and activities monitored through; remote surveillance of building behavior; central off-switch for appliances at home; central reporting of TBS performance and energy use.

Many of those services (e.g. reporting information regarding TBS performance, providing present, historical and predicted energy consumption data, occupancy detection, etc.) present a deeper focus in the field of Human-Building Interaction (HBI), which is among the research goals of OFFICE project. This observation is meant to underline the importance of considering the current and future outcomes of SRI research for useful insights on OFFICE studies.

3. Review of existing facilities and present projects

As mentioned in the previous chapters, OFFICE will be a test room where experiments about energy saving strategies, based on smart technologies and Human-Building Interaction (HBI) will be performed. A review of the scientific literature and other documentation on existing facilities and current projects is required to have a clear idea of the state of the art. The subjects to be investigated are the following: considering that in the tests the optimal balance between energy saving and occupants comfort must be sought, which are the features – design, materials, instrumentation, etc. – the facility should present? Which paths should be followed when defining different interaction strategies aimed at energy efficiency?

For tackling the issue of the laboratory features, different aspects must be considered: OFFICE aims at reproducing realistic working situations, therefore attention must be addressed to the occupants' perception of the indoor environment; in parallel, for the aim of the tests, environmental parameters need to be measured, and instrumentation for doing so must be provided. Most of the test facilities presented by Wagner et al. (2018) reproduce realistic environments and constitute therefore a source of knowledge about their features and the environmental measurements performed during the tests. Further knowledge about sensory equipment, in particular the devices employed in a test facility dealing with Human-Building Interaction can be acquired from the website of the Human-Building Interaction Lab, at Carleton University, Canada. Moreover, as illustrated in detail in chapter 5, despite being located inside a building, OFFICE facility presents some thermal requirements similar to those of an outdoor facility, and it will be adjacent to a transparent façade; the possibility of testing envelope elements is therefore envisaged. For this reason, the outdoor test facilities analysis proposed by Cattarin et al. (2016) should be evaluated. Information about the test facilities cited above are reported in section 3.1.

Concerning the strategies to be implemented in the test scenarios, an overview on HBI issue should be provided to understand which approaches are currently in use. Insights about HBI and user-centered approach in designing energy efficient buildings are provided by Shen (2015). With respect to existing facilities, the Human-Building Interaction Lab in Carleton University provides once again useful insights, as well as iHomeLab at Lucern University of Applied Sciences and Arts, where innovative interaction opportunities between building and occupants are displayed. Information concerning these research activities are described in section 3.2.

Exploring the local panorama of HBI innovation it is worth mentioning the experiments carried out within the project Human Observation Meta Environment (HOME) by UniToGO. The project develops in Torino as a field research activity taking place in university spaces, where occupants can interact with the buildings by means of natural interaction interfaces, such as gestures, movement and vocal indication. HOME project is now at an initial stage, which does not allow a detailed analysis of the experience, however, it is useful to check future progresses of this or other studies about HBI carried out locally.

3.1. Laboratory features and instrumentation

3.1.1. Laboratory approach in studying occupant behavior: a review of existing facilities (Wagner et al., 2018)

Buildings are made for people, and what both designers and occupants strive for is maximizing comfort. On the way towards smart buildings, which can carry out optimal responses to minimum-energy/maximum-comfort needs, studying occupants' behavior and understanding the drivers of their comfort is crucial. In the book Exploring Occupant Behavior in Buildings by Wagner, O'Brien and Dong (2017) one of the chapters is fully dedicated to Laboratory Approaches to Studying Occupants. Here, a range of existing test facilities is presented to display the experimental opportunities that simulations under precisely controlled conditions offer.

Seven out of ten facilities have been selected for the aim of this study. Information about their features, objectives of the experiments carried out, parameter measured during the tests, instrumentation, have been collected for obtaining indications for designing OFFICE room. Besides the review by Wagner et al. (2018), several papers presenting the facilities or reporting performed experiments, and online material made available by the educational institutions owning the labs have been taken into consideration. The main characteristics of the facilities as well as their study objectives are listed below.

- *International Centre for Indoor Environment and Energy (ICIEE)* – Danish Technical University (DTU), Denmark. The facility includes climate chambers and field laboratories whose dimensions span from 9 to 36 m^2; experiments and tests mainly deal with thermal comfort, air quality, air distribution, ventilation systems. The tests carried out in some of the climate chambers are performed using manikins, therefore the indoor space does not reproduce a realistic environment (**FIG.4A**). Materials for interior finishing are often chosen as low-emitting for a better air quality.
- *Controlled Environmental Chamber* – Center for the Built Environment (CBE), University of California at Berkeley, USA. The facility consists of an office-like chamber of about 30 m^2 for thermal comfort experiments and tests on different air distribution systems (**FIG.4B**). Natural ventilation is possible through operable windows. Four modular workstations are located in the central area of the room.
- *Indoor Environmental Quality Laboratory (IEQ Lab)* – University of Sydney, Australia. The two test chambers (25 and 60 m^2) with variable indoor design are

meant for examining how combinations of IEQ factors relate to comfort, productivity, and health of occupants (**FIG.4C**). Both rooms have windows facing an environmental corridor with lamps simulating the sunlight; moreover, the bigger room has operable windows to the outside allowing natural ventilation.

- *Laboratory for Occupant Behavior, Satisfaction, Thermal comfort and Environmental Research (LOBSTER)* – Karlsruhe Institute of Technology (KIT), Germany. The outdoor facility (**FIG.4D**) aims at studying adaptation and behavioral actions of occupants. It is positioned on a rotating structure which allows to avoid the direct solar radiation on the transparent façade during experiments. LOBSTER includes two identical rooms of 24 m^2 reproducing an office environment. The structure is timber frame and the envelope is made of prefabricated panels.
- *SinBerBEST Test Bed* – Berkeley Education Alliance for Research in Singapore (BEARS) Limited, Singapore. The configurable space of around 100 m^2 can be split into up to four rooms through moveable and interchangeable wall panels. The facility is designed for experiments on air quality, thermal and visual comfort (**FIG.4E**).
- *Institute for Energy Efficient Buildings and Indoor Climate, E.ON Energy Research Center* – RWTH Aachen University, Germany. The facility includes different kinds of labs, among which some climate chambers and a living lab office.
- *High Performance Indoor Environment Laboratory (HiPIE-Lab), Indoor Air Test Center (IATC), Modular Test Facility for Energy and Indoor Environments (VERU)* – Fraunhofer Institute for Building Physics (IBP), Germany. Laboratories for IEQ tests, investigation of air quality, and tests over façade systems (**FIG.4F**) and their effects on energy consumption.

According to the tests objectives the facilities are equipped with different typologies of Technical Building Systems and different parameters are monitored. Such information is summarized in **TAB.1** with the aim of providing a general overview of the reviewed facilities and a sort of index for prospective follow-ups.

FIG.4A. ICIEE –Test with a manikin.
Source: http://www.iciee.byg.dtu.dk/

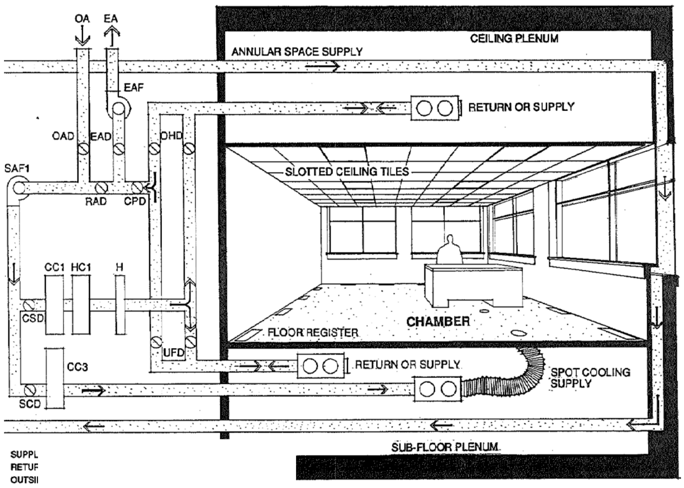

FIG.4B. CEC – Air flow schematic.
Source: Bauman and Arens (1988)

FIG.4C. IEQ – Environmental corridor.
Source: de Dear et al. (2013)

FIG.4D. LOBSTER – Outdoor rotating facility.
Source: Schweiker et al. (2014)

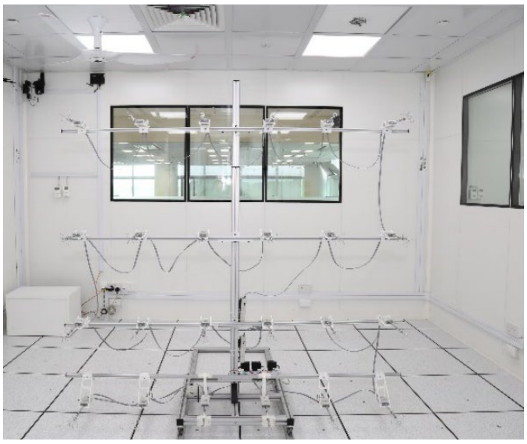

FIG.4E. SinBerBEST – Measuring equipment.
Source: http://sinberbest.berkeley.edu/

FIG.4F. VERU – Room for envelope elements tests.
Source: https://www.ibp.fraunhofer.de/

FACILITIES

Name	Location	Date of construction	Thermal comfort	Visual comfort	Air quality	Energy consumption	Occupant behavior
ICIEE	DTU, Denmark						
Climate chambers		1972 on	●				●
Field laboratories		2001 on	●		●		●
CEC	UC Berkeley, USA	1988	●		●	●	●
IEQ Lab	University of Sidney, Australia	2012	●	●		●	●
LOBSTER	KIT, Germany	2013	●				●
CREATE Tower - SinBerBEST Test Bed	University Town, Singapore	nf	●	●	●		
E.ON Energy Research Center	RWTH Aachen University, Germany	nf	●	●	●		
Indoor Env. Labs	Fraunhofer IBP, Germany	nf					
HiPIE-Lab, IATC			●	●	●		
VERU			●	●	●	●	

MEASURED VARIABLES

Name	Temperature: Indoor air	Temperature: Operative (indoor)	Temperature: Outdoor air	Relative Humidity: Indoor	Relative Humidity: Outdoor	Air Flow: Air velocity	Air Flow: Air exchange rate	Air Quality: CO2 concentration	Air Quality: VOC concentration	Light: Illuminance	Dynamic Envelope: Window open/closed	Dynamic Envelope: Shading system position	Physiology: Skin temperature	Physiology: Heart Rate	Heat: Solar heat gains	Heat: Internal loads
ICIEE																
Climate chambers	●	●	●	●	●	●	nf	nf	nf	nf			●	●	o	nf
Field laboratories	●	●	●	●	●	●	●	●	●	●	nf	nf	●	●	nf	nf
CEC	●	nf	●	●	●	●	●	nf	nf	nf	nf	nf	●	nf	nf	●
IEQ Lab	●	nf	●	●	nf	●	nf	●	●	●	nf	nf	●	●	nf	nf
LOBSTER	●	●	●	●	●	●	nf	nf	nf	nf	●	●	nf	nf	●	nf
CREATE Tower - SinBerBEST Test Bed	●	nf	●	●	●	nf	nf	●	nf	●			nf	nf	nf	nf
E.ON Energy Research Center	●	nf	nf	●	nf	nf	nf	●	●	nf	nf	nf	nf	nf	nf	nf
Indoor Env. Labs																
HiPIE-Lab, IATC	●	nf	nf	nf	nf	nf	nf	●	●	●	nf	nf	nf	nf	nf	nf
VERU	●	nf	nf	●	nf	nf	nf	nf	nf	●	nf	nf	nf	nf	●	nf

TECHNICAL BUILDING SYSTEMS

Name	Ventilation: Natural ventilation	Ventilation: Displacement ventilation	Ventilation: Piston flow ventilation	Ventilation: Mixing ventilation	Ventilation: (VAV) Variable Air Volume System	Ventilation: (CAV) Constant Air Volume System	Ventilation: (UFAD) Under Floor Air Distribution	Heating/cooling: Air condotioning	Heating/cooling: Radiant	Heating/cooling: Fan	Heating/cooling: Chilled Beam	Heating/cooling: Convectors	Lighting: Solar screens	Lighting: Daylight emulator	Lighting: General artificial lighting	Lighting: Spot artificial lighting
ICIEE																
Climate chambers		●	●	●	nf	nf	nf	●		●		nf			●	nf
Field laboratories	●	●	nf	●		●	●	●		●		●	nf		●	●
CEC	●	●	●	●	●		●	●		nf			nf		●	●
IEQ Lab	●	nf	nf	nf	●		●	●		●	●	nf	nf	●	●	nf
LOBSTER	●				nf	nf	●	●	●	●		●	●		●	nf
CREATE Tower - SinBerBEST Test Bed		●	nf		nf	nf	nf	●	●	nf	●		●	●	●	nf
E.ON Energy Research Center	nf	●	nf	nf	nf	nf	nf	●	●	nf	●	nf	nf	nf	nf	nf
Indoor Env. Labs																
HiPIE-Lab, IATC	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	●	●	nf
VERU	●	nf	nf	nf	nf	nf	nf	●	nf	nf	nf	nf	●		●	nf

Key: ● = present feature | nf = not found information about this feature

TAB.1. Overview of the controlled variables and the technical building systems used in the facilities.

Laboratories allow to perform experiments under carefully controlled conditions and measured variables can be easily isolated: for this reason, they are often preferred to in situ studies. Nevertheless, the authors recognise that, as far as human behavior is concerned, questions about the reliability of the occupant behavior in a lab may rise. An occupant who is aware of being under observation and in a transient situation might behave differently from everyday life.

For the aim of this study the facilities described by Wagner, O'Brien and Dong (2017) serve as a reference for the laboratory design and the technical systems, sensors and equipment to be included in the new EC_lab test room. Concerning the facilities design, the authors provide some recommendations: real windows to the outside should be included in the test room, since they are fundamental for inclusion of natural ventilation in the studies, and very important for the occupants' well-being; a solar shading system should be provided for preventing the space from overheating; flexible room partitioning should be preferred to fixed one for allowing different room spatial configurations; over-instrumentation should be avoided and sensory equipment should interfere as less as possible with the occupants' action and movement to limit the feeling of being observed. However, integrating sensors in the room interiors is not always easy; in fact, many environmental parameters need to be measured in an area close to the occupants or in the middle of the room (**FIG.4E**, **4F**).

3.1.2. Monitoring occupant's interaction with technical building systems: Human-Building Interaction Lab at Carleton University

A different approach is used in the Human-Building Interaction Lab at Carleton University where field studies on both indoor environment quality and occupant-building interaction are carried out. The monitoring is performed in three buildings of the university campus, thus allowing an extensive collection of data. The field studies performed at Carleton can be more accurate than average field studies because the monitored buildings have been designed as large scale experimental facilities, thus providing most of the rooms with sensors, actuators, and other equipment.

Many projects deal with occupant behavior modelling and its integration into building simulation. Concerning office environments, researchers are carrying out a project whose aim is developing an advanced control for offices, more flexible than the standard ones, and adapting to occupants and spaces (e.g. learning occupant preferences, considering visual properties of the space, etc.).

FIG.5 gives an overview of the sensors installed in many rooms in the campus. The main user interface is a thermostat measuring temperature, occupancy, relative humidity (RH), CO_2, with possibility of controlling lights and motorized window shades. It provides basic feedback to the occupants, such as measured temperature and RH. Further feedback is provided through a signal light located close to operable windows and suggesting to the occupants when to open or close the window (which is not motorized) according to the CO_2 level measured by the thermostat. The windows and doors opening/closing is monitored through contact sensors, while sensors for occupancy and illuminance are located on the ceiling. Electricity consumption due to the use of devices is measured through smart electrical outlets, while the energy used for the radiant heating system is measured thanks to flow meters and fluid flow temperature sensors.

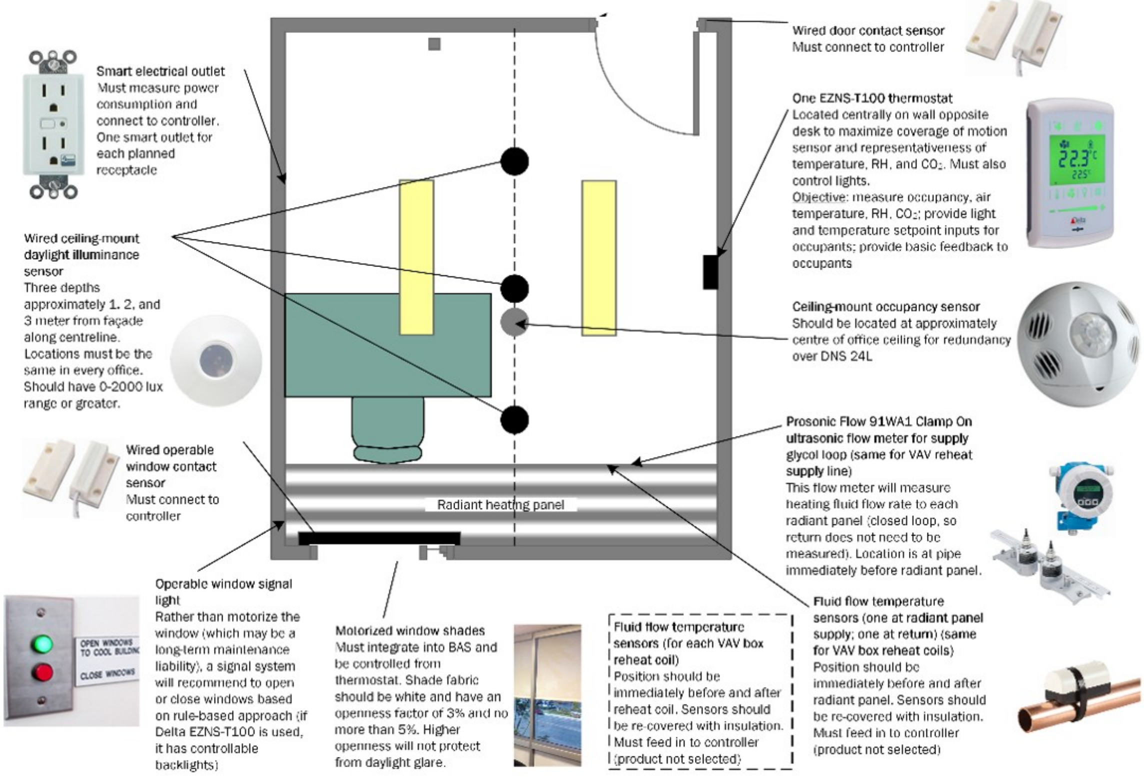

FIG.5. Overview of sensors, actuators, and other equipment installed in 27 rooms.
Source: https://carleton.ca/hbilab/facilities/

3.1.3. Outdoor test cells for building envelope experimental characterisation (Cattarin et al., 2016)

Cattarin et al. (2016) underline the importance of testing envelope elements in the present situation where buildings are required to be highly energy efficient. The energy performance of envelope elements can either be assessed in field tests – which are preferred for their proximity to real conditions – or in laboratory facilities – where measurements are more accurate, and it is possible to carry out comparative studies because of the replicability of the test settings. Outdoor test cells allow to combine the features of a controlled indoor environment with the interaction with real outdoor conditions (differently from indoor laboratories where the weather conditions are simulated). The authors propose a classification of outdoor test cells in two categories: comparative test cells, where twin rooms are used for running in parallel experiments under different conditions, and absolute test cells, where comparison of different elements performance can be provided through indices. In the latter group two subcategories are individuated: guarded test cells and calibrated ones. Both typologies have only one of the six walls directly exposed to outdoor weather conditions, while the remaining five are protected in order to minimize thermal exchange. In guarded cells those sides are surrounded by a conditioned buffering zone, referred to as guard zone; calibrated cells present instead a thick layer of thermal insulating material on five sides. As explained in Chapter 4, OFFICE experiments with different setups will not be carried out contemporarily; moreover, because of some of the framework conditions (see chapter 4), a buffering zone will surround the test room, therefore the facility will resemble a guarded test cell. For this reason, the three guarded test cells reviewed by Cattarin et al. (2016) are briefly described below.

- *Material Testing and Research (EMPA) – Duebendorf, Switzerland*. The facility presents two identical test cells (about 13 m^2 each) surrounded on five sides by an air-conditioned guard zone; each cell and the guard zone are provided with their own air handling unit (Manz et al. 2006). It is possible to install an external climate chamber on the façade to the outdoors.

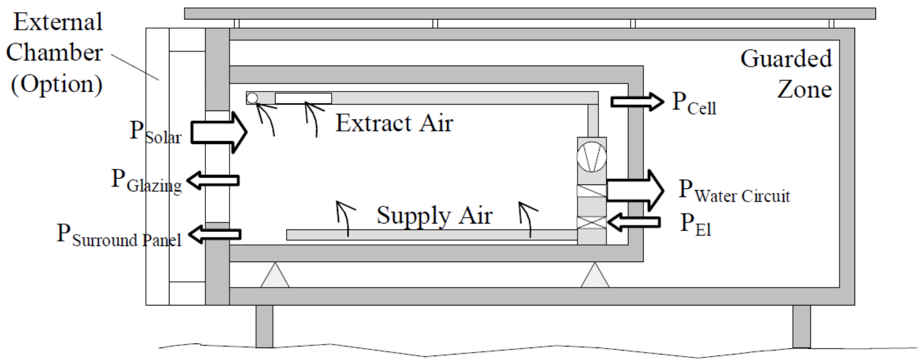

FIG.6. Concept of test facility with air conditioning of the cell, guarded zone, energy flows into and out of the test cell and optional external chamber. Source: Manz et al. (2006), p.

- *The Cube – Aalborg, Denmark.* The facility is meant for testing the performance of double skin façades with different kinds of ventilation and shading systems. The facility consists of four domains (Kalyanova and Heiselberg, 2008), which are named as: double-skin façade (DSF), experiment room, instrument room and plant room.

FIG.7. *The Cube*. Source: Kalyanova and Heiselberg. (2008), p.7.

The smaller DSF modules are operable and according to their opening pattern different effects on the indoor environment can be achieved (**FIG.8**).

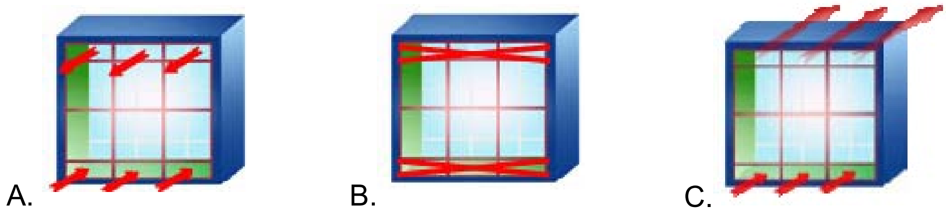

FIG.8. Operational modes of the DSF: external air curtain (A); transparent insulation (B); preheating mode (C). Source: Kalyanova and Heiselberg. (2008), p.32

- *MINIBAT – Cethil, France.* The facility consists of two identical cells (about 9 m^2 each). Five faces of the rooms are adjacent to a guard zone which is thermally controlled by a distribution air network (Gavan et al., 2010). The wall between the test cell and the guard zone is made of a polystyrene layer between two layers of plasterboard, and a layer of agglomerated wood. The sixth face of each cell is characterized by a double skin façade in which outdoor weather conditions (air temperature, solar radiation) can be simulated.

3.2. Human-Building Interaction

3.2.1. Human-Building Interaction (HBI): Design Thinking and Energy Efficiency (Shen, 2015).

The research has been carried out at the Center for Energy and Environment (CEE) in Minnesota, USA, and it focuses on the way occupants interact with building when using energy, and which direction Human-Building Interaction is expected to follow in the near future. The idea behind HBI research is adopting a user-centered approach to find the best strategies for achieving greater energy efficiency in the built environment. In fact, producing new opportunities for the occupants when interacting with the indoor environments through smart technologies can facilitate them in adopting energy efficient behaviors.

When dealing with strategies for encouraging users to save energy, the author refers to "Nudges" a book by Thaler and Sustain (2008) on how a planner can influence people's choices and behaviors. Among the principles altering people's behavior, defined by Thaler and Sustain (2008), and summarized by Shen (2015), there are two which are useful in the framework of OFFICE test scenarios definition. One of those principles is *Default*, i.e. the tendency of not acting to change the present conditions. With reference to occupant behavior in relation to energy management in buildings this means that often energy efficient behaviors are not adopted because of a matter of habit or a lack of confidence in changing the settings of the systems (e.g. using washing machine programs with warm water instead of setting the use of cold water). Building automation is a strategy for avoiding the necessity of deviating from the default option, since the default itself would be user-tailored. Another important principle is *Give feedback* because it allows the users to know if their behavior is poor or effective. The way it is provided affects the effectiveness in leveraging people's behavior. Feedback can be in different forms (textual, graphical, audio, etc.), it can include both absolute and comparative data, and it can be combined with gamification strategies for a obtaining a stronger motivation for energy-saving behavior based on competition and social pressure.

3.2.2. Think tank and research center for building intelligence: iHomeLab at HSLU, Luzern

Differently from the facilities presented above, the iHomeLab at HSLU does not deal directly with laboratory tests (which are carried out in other facilities at HSLU). However, for the aim of this study it is interesting mentioning it as a facility where innovative technologies in the Human-Building Interaction field are tested and the opportunities they offer are presented to the public. The technologies tested in iHomeLab are meant to maximize the uses' comfort while interacting with the technical building systems and at the same time to take care of the occupants' safety and of the energy consumption in the building. Some examples of implemented technologies are listed below.

- Vocal interaction with a virtual butler, being connected with all the technical building systems. Through a mobile application the occupant can control the systems by simply "asking" to switch on lights, or to have a lower temperature in the room.
- Automated functioning of some appliances according to occupant's location, detected thanks to wearable devices. For example, if the occupant is watching movie on a screen located in a room and then needs to move to another room,

the movie is automatically displayed on a screen in the new room or on a mobile device the occupant is carrying. Moreover, the detection of occupant's position combined with vocal interaction can be employed for safety reasons: if an elderly person falls when alone in the house and he/she does not respond to vocal signals, the system can automatically call for help.

- Visual and real-time feedback about energy use. Displaying energy consumption data or notifying the user when they are particularly high are strategies meant for raising awareness and might positively affect user's readiness to save energy, especially when the occupant is paying for the energy used in the building.

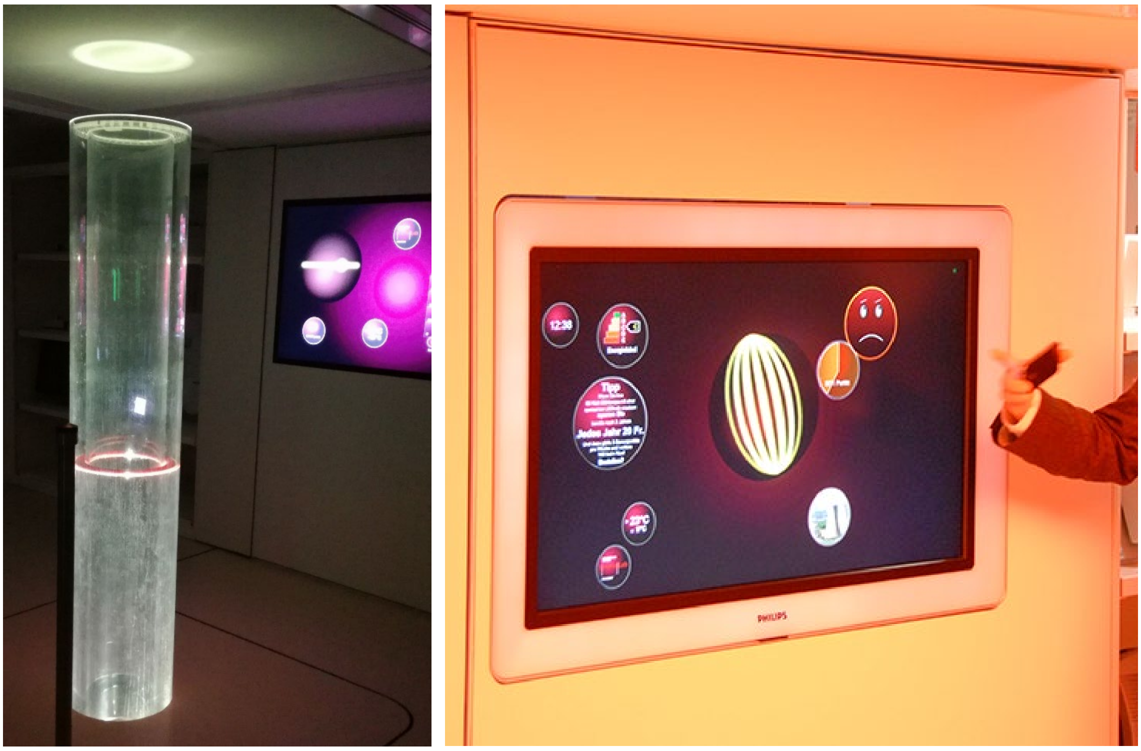

FIG.9. Visual feedback on energy use. On the left: the higher the water level, the higher the current energy use. Source: photography by Letizia Garbolino. On the right: real-time information on energy use, temperature, etc. and notification about how efficient the current behavior is, are displayed on screen. Source: https://www.hslu.ch/de-ch/technik-architektur/forschung/kompetenzzentren/ihomelab/

Some interaction methods described above might have useful application in smart office environments. For instance, the screens activation according to the occupant location could be beneficial when following a conference call, while a visual feedback within the room could raise the attention of people being focused on working activities, who would hardly remind adopting energy-efficient behaviors otherwise.

4. OFFICE targets: a facility for research, policy making, and technology in the energy field

In the OFFICE facility, studies about the energy saving effects of various Human-Building Interaction modes and Technical Building Systems will be carried out. A typical office environment will be reproduced to test how the adoption of different interaction methods, with greater or smaller control opportunities for occupants, leads to variations in energy consumption. The aim of the studies is defining the most energy-efficient scenarios with the inclusion of smart technologies in outdated buildings. The results will be used for defining local energy planning strategies for the renovation of office buildings.

According to the European Directive 2010/31/EU "buildings occupied by public authorities and buildings frequently visited by the public should set an example by showing that environmental and energy considerations are being taken into account". However, considering the current state of many public buildings in Italy, a quite vast intervention is required, and it is, in part, already taking place. Besides the need for improving the energy performance by retrofitting them with more up to date building technologies, an efficient management of the Technical Building Systems is necessary. For this purpose, innovative and smart technologies for building automation and control, must be integrated.

With respect to Città Metropolitana di Torino, the local administration aims at taking action on the heritage of around 800 public buildings – such as offices, schools, hospitals, etc. – through policies of local energy planning. The policies should refer to the introduction of innovative technologies and adoption of best practices. For doing so, local studies on public buildings heritage (energy use, adopted architectural technologies, location, etc.) should lay the foundations for energy policies development. Within this panorama, EC_lab is set and defined by Politecnico di Torino (2018) as a physical space where industry, research, and local administration can cooperate facing energy challenges.

4.1. Test scenarios

OFFICE will be designed for allowing the setup of different test scenarios: a Trial Scenario will be used as a reference for standard energy consumption in a non-smart office environment; the actual test scenarios will instead lay their foundations on a set of features variously combined. Those combinations would originate a range of setups, spanning between two extremes:

- *Feedback Scenario*, where the Technical Building Systems are mostly under occupants' control, and energy savings are up to the adoption of a smart occupant behavior, triggered by the use of persuasive technologies (Fabi, Spigliantini, Corgnati, 2016), i.e. the provision of real-time feedback on energy usage/energy savings to the occupants for encouraging them to modify their behaviors;

- *Automated Scenario*, where the control and operation of the Technical Building Systems are completely automated, thus optimized by algorithms in relation to energy performance, comfort and health criteria.

The first category of tests lays its foundation on occupant behavior field of studies – broadly investigated in recent years – whose aim is enhancing energy performance of buildings acting on occupants' awareness-raising and education about how they use energy. The positive aspects of this approach are both its cost-effectiveness (it can be implemented even without the employment of expensive technology) and its positive effect on occupants, who keep the perception of control over the systems – which has been shown, according to several studies, to be a driver of indoor environment acceptability – and gain awareness in the relevance of their pro-social action about energy saving (Fabi, Spigliantini, Corgnati, 2016). The challenge about this approach is understanding whether building occupants are willing to change their behavior for the sake of environmental sustainability, even when they are not directly economically involved – i.e. they are not paying for the energy bill at their workplace.

The second category relies on the transformation towards digitization that buildings are going to face in the near future or are already facing. Concerning office environments, their transition to smart workplaces will not only affect the energy performance of the building but it will transform the way people do their work, providing the conditions for enhanced productivity, facilitating cooperation and aggregation, or overcoming the necessity of physical presence in a specific location (with positive effects on the reduced demand for mobility). Coming back to energy and indoor environment related aspects of building automation, the challenge of this approach consists in making sure the occupant comfort is actually met. Comfort-related studies demonstrated that controlling a series of environmental parameters – temperature, relative humidity, air velocity, lighting level, noise level to name a few – allows the creation of a comfortable indoor environment according to standardized values. However, human comfort also depends on personal preferences, and acceptance of environmental conditions is strongly affected by psychological factors. For instance, a study by Schweiker, Hawighorst, and Wagner (2016) proved that personality traits affect thermal sensation and preference, and drive occupants to different behavioral patterns. According to Schweiker and Wagner (2016) behavioral patterns and perceived comfort are also influenced by occupancy of the indoor environment; for example, a higher occupancy can discourage occupants to take action for changing indoor conditions. Meinke et al. (2016) demonstrated that providing feedforward information to the occupants – i.e. making them aware of the consequences different adaptive-comfort actions (opening a window, switching a fan on, etc.) would have on energy efficiency – can increase their thermal acceptance, thus helping face overheating problems. Moreover, in an environment where indoor climate is automatically controlled, occupants tend to have higher expectations of comfort, while in absence of automated control they tend to be more tolerant towards variations of the environmental conditions.

The research conducted in OFFICE will be aimed at finding the balance between the education of smart occupants and the implementation of smart office environment solutions, in terms of cost-effective strategies, driving the local energy planning towards workplaces being more sustainable for the environment, the society, and the individual. The connections among the actors involved in OFFICE experience, their objectives and roles within the research are displayed in **FIG.10**.

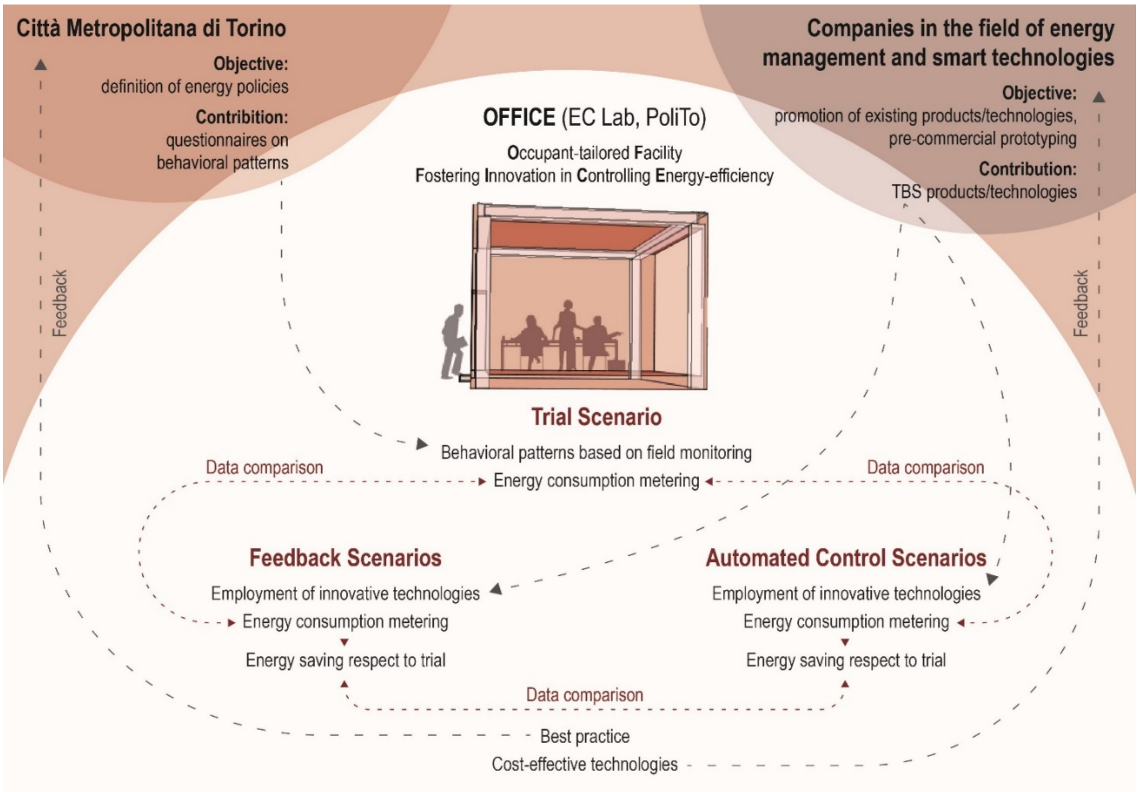

FIG.10. Actors involved in OFFICE studies and their role.

4.2. Trial Scenario

Occupants of real office environments owned by Torino Municipality are interviewed about their behavior when interacting with the Technical Building Systems at their workplace (e.g. when and for how long they keep windows open, whether and when they adjust the shading systems, under which conditions they switch on/off the heating/cooling system, etc.). The Trial Scenario consists in reproducing in OFFICE facility the behavioral patterns described by the interviewees: this operation might be done either manually or through automated control of the Technical Building Systems. During this test phase it is not essential the facility is occupied.

In this phase energy use is measured (both in terms of electrical loads and heat) and energy consumption data is recorded with the aim of obtaining reference data for comparison with data from the other test scenarios.

4.3. Feedback and Automated Scenarios

In the Feedback Scenarios, energy efficiency matters are tackled acting on occupants' behavior and encouraging its change. People working in the facility have manual control of the Technical Building Systems. Feedback on energy consumption and behavioral advice for increasing energy efficiency is provided. The occupant directly interacts with all the systems and receives feedback about their use; it is convenient to receive all feedbacks through a unique interface, for example a mobile application. The feedback consists in providing real-time energy consumption data, comparison with standard/average data and notification when energy use is too high; in that case behavioral advice is provided (e.g. "The heating is working despite the set indoor temperature has been reached, if you still feel cold you could check your clothing level", "The window has been kept open for fifteen minutes, you should either close it or switch the cooling system off"). Feedback is provided thanks to data from a series of connected sensors integrated in the facility as fixed instrumentation, described in Chapter 4. User-systems interaction works manually through actuators (e.g. thermostats, light switches and dimmers, shading system controllers, etc.) which can be selected for each specific test, and the indoor setup of the room adjusted accordingly.

In the automated scenario the occupants do not need to directly manage the Technical Building Systems: indoor conditions, occupants' activity, and systems operation are monitored by sensory and measuring equipment, so as to consequently set the operation of the TBS. This is allowed by the presence of a Building Automation and Control System (BACS). For instance, occupancy will be monitored so that when the room is empty heating, cooling, lighting, are switched off; moreover, occupancy patterns might be recorded to better adjust the heating/cooling time schedule. Or even, a further possibility is monitoring the position of the occupants in the room to take action close to the occupied workstations (e.g. switching off the unused lights or switching on the monitor which is closest to the occupant).

As mentioned above, a scenario based on manual control of the technical building systems and feedback and one characterized by full automation are considered as extremes of a range of scenarios meant to test different digitization levels. As the automation level of TBS increases, the occupants should make efforts in changing their behavior, so less feedback is required, or the kind of information provided needs to be different. For example, in a scenario where the occupant has low control on the temperature settings, a notification on the current state and energy use of the heating/cooling system might raise the acceptance of the indoor conditions. Considering the SRI research as a reference, the feedback-based, manual scenario and the fully automated one could be set up by respectively implementing the lowest and the highest functionality level of each service identified in the catalogue. However, only six out of the ten domains of service included in the SRI definition should be considered for OFFICE facility: *heating*, *cooling*, *ventilation*, *lighting*, *dynamic building envelope*, *monitoring and control*. The remaining domains – *domestic hot water*, *energy generation*, *demand side management*, *electric vehicle charging* – would not suit tests carried on in one single room. The services considered for the aim of this dissertation and the related functionality levels are reported in **TAB.2A**, **2B**, **2C**, **2D**. Each Smart Ready Service can assume from three to five different functionality levels: in most cases level 0 corresponds to no automatic control; as the functionality level increases the control of the TBS is determined by one or several variables, by self-learning algorithms and predictions about behavioral patterns, by the coordinated operation of different services, etc. The range of scenarios spanning from the least to the most automated includes all the possible combinations of functionality levels of the selected services.

The tests will be run by defining a set of scenarios, providing occupants to perform office activity, and monitoring the energy consumption of each test for calculating the savings with respect to the trial scenario. The occupants might be interviewed about how they value the quality of the Human-Building Interaction. The test procedure will lead to the identification of the most effective strategies (in terms of costs, saved energy, time of implementation, impact on the occupants, etc.) for the definition of local energy policies. Moreover, companies taking part in the tests will have the chance to promote the products which showed to be better performing during the tests. In fact, according to the definition of Smart Ready Service by Verbeke et al. (2018) the services included in the catalogue are defined in a technology neutral way. This allows, once the functionality levels to be implemented in a test scenario are selected, to test different technologies in the same scenario, thus comparing the performances of the products.

Code	Service group	Smart ready service	Functionality level 0	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
Heating-1a	Heat control - demand side	Heat emission control	No automatic control	Central automatic control (e.g. central thermostat)	Individual room control (e.g. thermostatic valves, or electronic controller)	Individual room control with communication between controllers and to BACS	Individual room control with communication and presence control
Heating-1b		Emission control for TABS (heating mode)	No automatic control	Central automatic control	Advanced central automatic control	Advanced central automatic control with intermittent operation and/or room temperature feedback control	
Heating-1c		Control of distribution fluid temperature (supply or return air flow or water flow) - Similar function can be applied to the control of direct electric heating networks	No automatic control	Outside temperature compensated control	Demand based control		
Heating-1d		Control of distribution pumps in networks	No automatic control	On off control	Multi-Stage control	Variable speed pump control (pump unit (internal) estimations)	Variable speed pump control (external demand signal)
Heating-1e		Intermittent control of emission and/or distribution - One controller can control different rooms/zones having same occupancy patterns	No automatic control	Automatic control with fixed time program	Automatic control with optimum start/stop	Automatic control with demand evaluation	
Heating-1f		Thermal Energy Storage (TES) for building heating (excluding TABS)	Continuous storage operation	Time-scheduled storage operation	Load prediction based storage operation		
Heating-1g		Building preheating control	No automatic control	Program heating schedule in advance	Thermostat self-learning user behavior (presence, setpoint)		
Heating-2a	Control heat production facilities	Heat generator control (for combustion and district heating)	Constant temperature control	Variable temperature control depending on outdoor temperature	Variable temperature control depending on the load (e.g. depending on supply water temperature set point)		
Heating-2b		Heat generator control (for heat pumps)	On/Off-control of heat generator	Multi-stage control of heat generator capacity depending on the load or demand (e.g. on/off of several compressors)	Variable control of heat generator capacity depending on the load or demand (e.g. hot gas bypass, inverter frequency control)	Variable control of heat generator capacity depending on the load AND external signals from grid	
Heating-2c		Sequencing of different heat generators	Priorities only based on running time	Priorities only based on loads (water boiler, heat pump)	Priorities based on generator efficiency and characteristics (e.g. multiple carriers, solar, gas, wood, etc)	Load prediction based sequencing	
Heating-2d		Heat system control according to external signal (e.g. electricity tariff, gas pricing, load shedding signal etc.)	No automatic control based on external signals	Heat system control according to external signals (tariff, availability of renewables, etc.)	Heat system control according to external signals combined with internal signals (predicted demand, temperature etc.)		
Heating-2e		Control of on-site waste heat recovery fed into the heating system (e.g. excess heat from data centers)	No heat recovery control	Heat recovery on/off control based on availability	Variable control of waste heat recovery (modulating power based on needs and waste heat availability)	Variable control of waste heat recovery with possibility to store excess heat or time shift heat recovery	
Heating-3	Information to occupants and facility managers	Report information regarding HEATING system performance	None	Indication of actual values (e.g. temperatures, submetering energy usage)	Actual values and historical data	Performance evaluation including forecasting and/or benchmarking	Perform+B1:J14ance evaluation including forecasting and/or benchmarking; also including predictive management and fault detection

TAB.2A. Services and functionality levels for heating. Source: SRI 1st technical study. Annex A.

Code	Service group	Smart ready service	Functionality level 0	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
Cooling-1a	Cooling control - demand side	Cooling emission control	No automatic control	Central automatic control	Individual room control REF	Individual room control with communication between controllers and to BACS	Individual room control with communication and presence control
Cooling-1b		Emission control for TABS (cooling mode)	No automatic control	Central automatic control	Advanced central automatic control	Advanced central automatic control with intermittent operation and/or room temperature feedback control	
Cooling-1c		Control of distribution network chilled water temperature (supply or return)	Constant temperature control	Outside temperature compensated control	Demand based control		
Cooling-1d		Control of distribution pumps in networks	No automatic control	On off control	Multi-Stage control	Variable speed pump control (pump unit (internal) estimations)	Variable speed pump control (external demand signal)
Cooling-1e		Intermittent control of emission and/or distribution	No automatic control	Automatic control with fixed time program	Automatic control with optimum start/stop	Automatic control with demand evaluation	
Cooling-1f		Interlock between heating and cooling control of emission and/or distribution	No interlock	Partial interlock (dependant of the HVAC system)	Total interlock		
Cooling-1g		Control of Thermal Energy Storage (TES) operation	Continuous storage operation	Time-scheduled storage operation	Load prediction based storage operation		
Cooling-2a	Control cooling production facilities	Generator control for cooling	Constant temperature control	Variable temperature control depending on outdoor temperature	Variable temperature control depending on the load		
Cooling-2b		Sequencing of different cooling generators	Priorities only based on running times	Priorities only based on loads	Priorities based on generator efficiency and characteristics	Load prediction based sequencing	
Cooling-3	Information to occupants and facility managers	Report information regarding cooling system performance	None	Indication of actual values (e.g. temperatures, submetering energy usage)	Actual values and historical data	Performance evaluation including forecasting and/or benchmarking	Performance evaluation including forecasting and/or benchmarking; also including predictive management and fault detection

TAB.2B. Services and functionality levels for cooling. Source: SRI 1st technical study. Annex A.

Code	Service group	Smart ready service	Functionality level 0	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
Ventilation-1a	Air flow control	Supply air flow control at the room level	No ventilation system or no automatic control	Time control	Occupancy detection control	Demand control based on air quality sensors (CO2, VOC,RH,…)	
Ventilation-1b		Adjust the outdoor air flow or exhaust air rate	Fixed OA ratio / OA flow	Staged (low/high) OA ratio / OA flow (time schedule)	Staged (low/high) OA ratio / OA flow (presence)	Variable control	
Ventilation-1c		Air flow or pressure control at the air handler level	No automatic control	On off time control	Multi-stage control	Automatic flow or pressure control (without reset)	Automatic flow or pressure control (with reset)
Ventilation-2a	Air temperature control	Room air temp. control (all-air systems)	on-off capacity control	variable capacity control	Demand control		
Ventilation-2b		Room air temp. control (Combined air-water systems)	No coordination	Coordination			
Ventilation-2c		Heat recovery control: prevention of overheating	Without overheating control	Modulate or bypass heat recovery based on sensors in air exhaust	Modulate or bypass heat recovery based on multiple room temperature sensors or predictive control		
Ventilation-2d		Supply air temperature control	No automatic control	Constant set point	Variable set point with outdoor temperature compensation	Variable set point with load dependant compensation	
Ventilation-3	Free cooling	Free cooling with mechanical ventilation system	No automatic control	Night cooling	Free cooling	H,x- directed control	
Ventilation-4	MV system operation	Heat recovery control: icing protection	Without icing protection control:	With icing protection control:			
Ventilation-5		Humidity control	No automatic control	Dew point control	Direct humidity control		
Ventilation-6	Feedback - Reporting information	Reporting information regarding IAQ	None or only temperature reporting	Air quality sensors (e.g. CO2) and central monitoring	Real time information of IAQ available to occupants	Real time information of IAQ available to occupants + suggesting triggers to action	
Lighting-1a	Artificial lighting control	Occupancy control for indoor lighting	Manual on/off switch	Manual on/off switch + additional sweeping extinction signal	Automatic detection (auto on / dimmed or auto off)	Automatic detection (manual on / dimmed or auto off)	
Lighting-1b		Mood and time based control of lighting in buildings	Manual on/off	Programmed control	Automated or mobile triggered detection		
Lighting-2	Control artificial lighting power based on daylight levels	Control artificial lighting power based on daylight levels	Manual (central)	Manual (per room / zone)	Automatic switching	Automatic dimming	Scene-based light control (during time intervals, dynamic and adapted lighting scenes are set, for example, in terms of illuminance level, different correlated colour temperature (CCT) and the possibility to change the light distribution within the space according to e. g. design, human needs, visual tasks)

TAB.2C. Services and functionality levels for controlled ventilation and lighting. Source: SRI 1st technical study. Annex A.

Code	Service group	Smart ready service	Functionality level 0	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
DE-1	Window control	Window solar shading control	No sun shading or only manual operation	Motorized operation with manual control	Motorized operation with automatic control based on sensor data	Combined light/blind/HVAC control	Predictive blind control (e.g. based on weather forecast)
DE-2		Window open/closed control, combined with HVAC system	Manual operation or only fixed windows	Open/closed detection to shut down heating or cooling systems	Level 1 + Automised mechanical window opening based on room sensor data	Level 2 + Centralized coordination of operable windows, e.g. to control free natural night cooling	
DE-3		Changing window spectral properties	Individual window control	Automized control	Integrated control with other systems such as heating and lighting		
MC-1	HVAC interaction control	Heating and cooling set point management	Manual setting room by room individually	Adaptation from distributed / decentralized plant rooms only	Adaptation from a central room	Adaptation from a central room with frequent set back of user inputs	
MC-2		Control of thermal exchanges	None	Management of heat/cold exchange among zones within one building or among different buildings - present in parts of the building	All occupied area has management of heat/cold exchange among zones within one building or among different buildings		
MC-3		Run time management of HVAC systems	Manual setting (plant enabling)	Individual setting following a predefined time schedule including fixed preconditioning phases	Individual setting following a predefined time schedule; adaptation from a central room; variable preconditioning phases	Control of run time management by artificial intelligence	
MC-4	Fault detection	Detecting faults of technical building systems and providing support to the diagnosis of these faults	No central indication of detected faults and alarms	With central indication of detected faults and alarms	With central indication of detected faults and alarms / diagnosing functions		
MC-5	Feedback - Reporting information	Reporting information regarding current energy consumption	None	Indication of actual values only (e.g. temperatures, meter values)	Trending functions and consumption determination	Analysing, performance evaluation, benchmarking	
MC-6		Reporting information regarding historical energy consumption	None	Indication of actual values only (e.g. temperatures, meter values)	Trending functions and consumption determination	Analysing, performance evaluation, benchmarking	
MC-7		Reporting information regarding predicted energy consumption	None	Indication of actual values only (e.g. temperatures, meter values)	Trending functions and consumption determination	Analysing, performance evaluation, benchmarking	
MC-9	TBS interaction control	Occupancy detection: connected services	None	For individual functions, e.g. lighting	Centralised detection which feeds in to several TBS such as lighting and heating		
MC-10		Occupancy detection: space and activity	No occupancy detection present	Occupancy detection can determine presence in room	Occupancy detection can determine average number of people in space	Occupancy detection can determine the actual number of people in a space	Occupancy detection can determine position of people in space (e.g. behind desk)
MC-11	Central control of energy consumers	Remote surveillance of building behaviour	Not present	Remote control of main TBS	Remote control of main TBS with centralised occupancy detection	Remote control of main TBS with centralised occupancy detection, automatic non-occupancy default settings and user alerts	
MC-12		Central off-switch for appliances at home	None	simple off switch	off switch with ability for remote operation	secquence of deactivation for load optimisation	
MC-13	Feedback - Reporting information	Central reporting of TBS performance and energy use	None	Real time indication of energy use per energy carrier	Real time indication of sub-metererd energy use or other performance metrics for at least 2 domains	Real time indication of sub-metererd energy use or other performance metrics for all main TBS	

TAB.2D. Services and functionality levels for dynamic building envelope and monitoring and control.
Source: SRI 1st technical study. Annex A.

5. Designing OFFICE

In the previous chapters several considerations on the context in which OFFICE is going to be developed have been proposed: the context has been clarified, the international policy panorama has been analyzed, existing facilities and recent studies have been reviewed, and finally the test objectives have been stated. These considerations suggest the requirements the facility should be designed upon and allow defining it as a controlled environment realistically reproducing an office where diverse instrumentation can be easily integrated, operated and stored by means of constructive elements allowing setup flexibility. The facility envisages the possibility of new future employments by means of a design facilitating the modification of its features. Transforming the requirements into design solutions means dealing with the constraints characterizing the specific case. The present chapter describes the requirements, displays the constraints, and proposes design solutions for OFFICE. Despite this dissertation mainly deals with aspects related to the spatial organization and architectural features of the facility, some considerations about the sensory equipment the laboratory should have, are displayed with reference to the existing facilities review. The main focus of this analysis does not deal with technical detail of the sensors, but rather with the disposition of the sensors within the environment.

The design solution presented in this chapter are illustrated with schemes, the complete layout of the facility design can be found in the Appendix.

5.1. OFFICE requirements

5.1.1. Flexible setup

As explained in Chapter 4, the tests performed in OFFICE envisage the creation of scenarios presenting different interactions between occupant and building. On one side, the way the services are offered to the occupants will vary: for instance, the technology used for providing the heating in the trial scenario (reproducing a real situation) will not always correspond to those employed in the test scenarios; or even, within the same technology, different kinds of actuators could be implemented. On the other side, the way occupants manage the systems will vary as well: different automation levels require a more or less interactive interface, deployed in widespread positions or concentrated. The opportunity of easily applying different methods for providing the services requires freedom in choosing where the actuators and outlets of the technical building systems will be located within the room. For instance, a radiant system for heating and cooling might be included in the floor, in the walls, or in the ceiling. The ventilation – both mechanical and natural – might be provided either from a top or bottom area. For allowing such variations, the facility must envisage the positioning of the systems terminations in every area of the room, and ensure they are easily accessible through the interior finishing surface. Hence, that surface must be reversibly installed and allow the integration of actuators, outlets, and interface devices. The setup flexibility can be addressed through the use of modular elements.

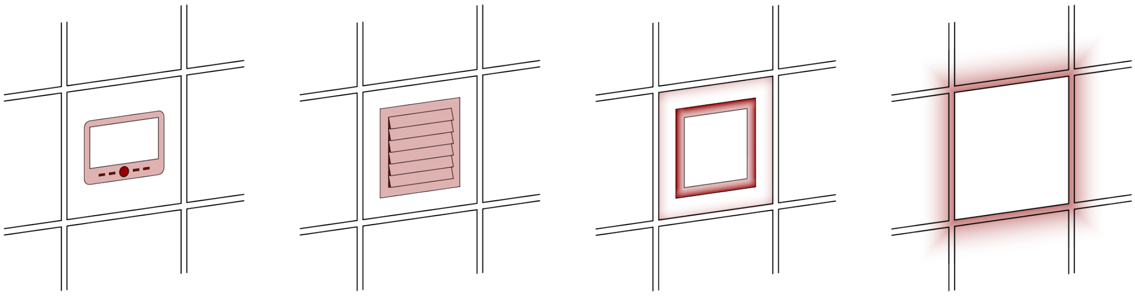

FIG.11. Inner envelope modules can integrate different kind of TBS actuators and terminals, sensory equipment, HBI instrumentation.

5.1.2. Adaptability to future arrangements

OFFICE originates from the need by EC_lab of creating a laboratory space addressing specific objectives and case studies, a space to which spatial and economic constraints are associated. However, once the first research task is completed, the facility will be employed in a new one: the modified conditions – the project scale, new actors involved, increased funds, etc. – might produce the need and availability of a broader test slot within EC_house, thus the necessity of expanding the facility.

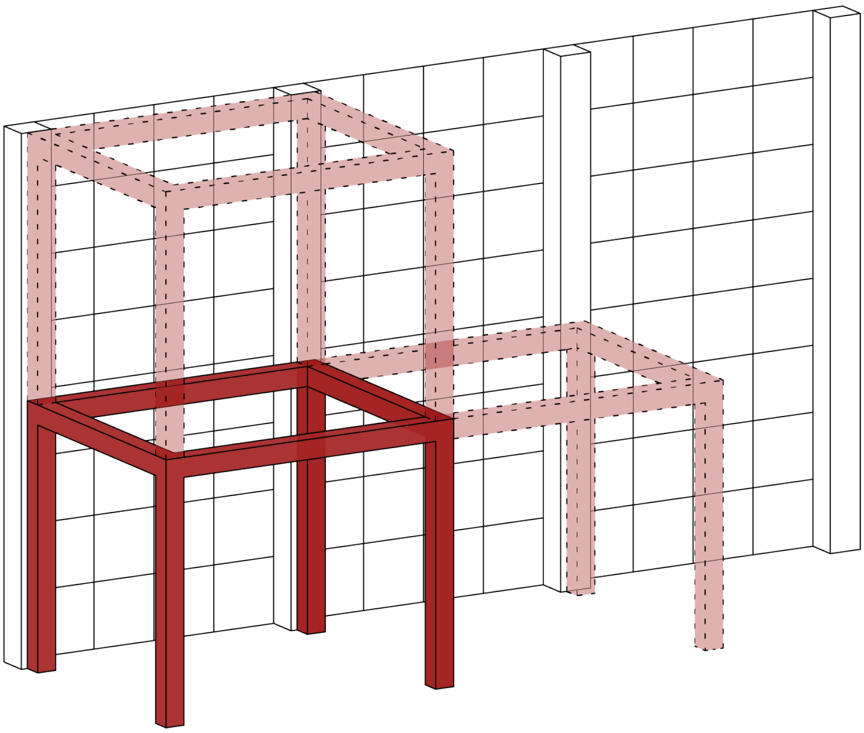

FIG.12. The overall structure of the facility should fit the modularity or EC_house laboratory space.

Therefore, the employed constructive technologies must allow relatively easy modifications in the room overall structure. As in the case of setup flexibility, reversible construction technologies and modularity represent the most functional solutions.

Moreover, the use of constructive elements which can be employed again after dismantling is a plus of building sustainability, because it avoids material waste and produces energy savings within the life-cycle of the product. Finally, if the room fits to the modularity of the space it is built in – for instance it fills the span between two pillars – it will be easier to expand it according to that modularity.

5.1.3. Instrumentation integrability, management and setting

The requirement of setup flexibility highlights the importance of being able to integrate diverse services and technologies in the facility. However, another requirement is tightly connected to the matter: the facility must be set up to integrate a large amount of technical building systems equipment – redundancy is necessary for being able to offer the same service through different technologies – as well as to allow their setting and maintenance, and to have control over the measuring equipment and the tested technologies. As underlined with reference to the flexible setup requirement, it is necessary to position the systems terminations according to the needs of each test, which means the systems wires and pipes must be able to reach any area in the room. For doing so, beyond the shell of the occupied room – i.e. the actual office – a void space for distributing the systems will be envisaged. Furthermore, the operators need to have access to devices and machinery for setting and controlling the test conditions. The measuring equipment connected to the sensors, computers for managing the smart services and technologies, and apparatuses of the systems will be located and managed in a dedicated space, separated from the office environment.

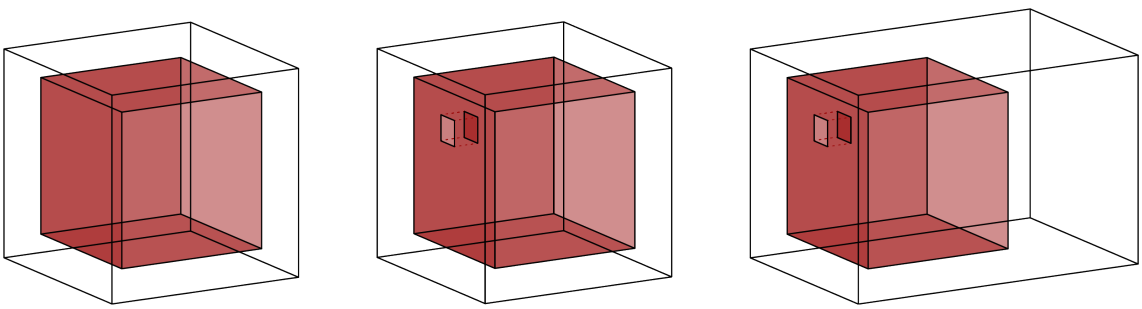

FIG.13. Important features of the spatial organization are defined by the needs related to instrumentation and systems management.

5.1.4. Controlled environment

The main OFFICE test objective is studying Human-Building Interaction while testing technologies for energy efficiency: most of those technologies will integrate sensors for their automated functioning. However, being comfort the main driver for occupant action towards the systems, such experiments become more meaningful if accurate information about the environmental parameters (which are among the comfort drivers) is provided. Moreover, providing the facility with reliable, fixed sensory equipment allows to check the reliability of the technologies under test. Making OFFICE a controlled environment means on one side monitoring a set of parameters of the indoor environment (dealing with thermal and visual conditions, air quality, etc.) while running the tests, on the other side it implies to regulate the interaction with neighboring spaces in terms of thermal exchange. The slot intended to house OFFICE is part of a broad indoor space adjacent on one side to a transparent façade. If the room was part of a larger working environment it could be assumed that thermal exchange with neighboring offices would be negligible. But the function of the space which surrounds the facility is currently undetermined, and so is its thermal condition; hence, a solution for minimizing thermal exchange must be adopted. The observation of outdoor facilities reviewed by Cattarin et al. (2016) provides useful insights about test rooms where thermal exchange is avoided through five of the six sides, so as to only observe the effects of thermal exchange through the remaining side. Applying such method to OFFICE allows the test of envelope elements: operable windows, shading systems, double skin façades, to name a few.

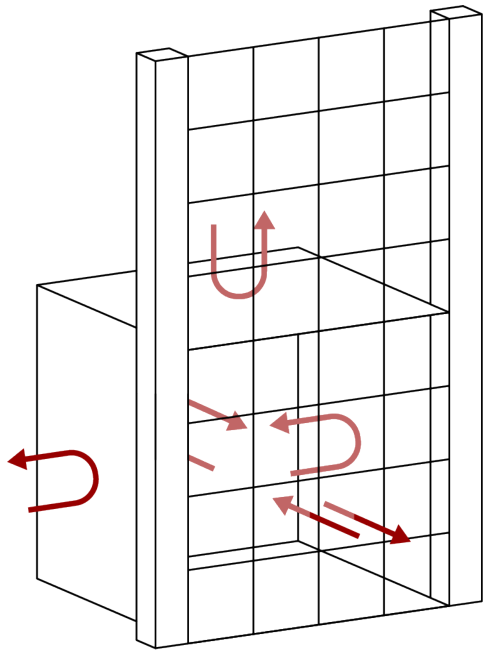

FIG.14. The thermal exchange through the envelope is either controlled or measured.

5.1.5. Realistic environment

The tests run in OFFICE must take into account the central role of the occupant. In fact, when occupants have some control over the TBS operation, their behavior is the enabler of energy performance, since even high performing technologies, if used incorrectly, can fail to meet the expected results. On the other hand, adopting building automation to ensure energy performance goals are met, entails the risk of occupants' disappointment because of their high expectations or because of the difficulty to accept the lack of control over the systems. To ensure the occupant behavior during tests is reliable and similar to that adopted in an everyday situation, OFFICE must reproduce as much as possible a realistic office environment. Realistic environments are often reproduced in the reviewed facilities whose tests deal with occupant behavior, so that the performing (or not performing) of actions is not affected by the occupant's feeling of being in a laboratory.

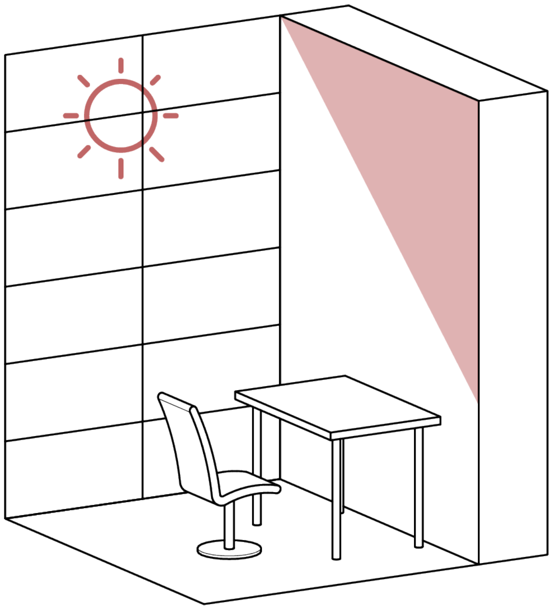

FIG.15. Visual contact with the outside, natural light and suitable furniture and finishing strongly affect the perception of an indoor environment.

For instance, the presence of instrumentation within the occupied environment, generating the impression of being under test, could negatively influence the perception of comfort. Moreover, when subjects know they are in a transient situation, they tend to act differently than how they would normally do and may accept discomfort because they know the environment they are in is not a permanent one. So, they might interact less or differently than usual with the systems. In OFFICE Human-Building Interaction modes for application in local realities will be tested, therefore it is of utmost importance to make the occupants feel as they were performing everyday actions, thus obtaining results that with high probability get close to those of a real office. Hence, the features of the room interiors should resemble as much as possible a normal office, presenting typical office furniture and equipment, avoiding over-instrumentation and integrating the sensory equipment – where possible – in the interior finishing elements or in the furniture. Moreover, as underlined by Wagner et al. (2018), the feelings of the occupants towards the indoor environment would be more positive if they could keep visual connection with the outdoors or other occupied rooms. A further requirement for the interiors of OFFICE might be represented by its location within an existing building, hosting other working spaces. Adapting the facility to the interior design of EC_house – which envisages the employment of white and transparent walls for maximizing the benefit of natural light – would make the room adequately integrated to the aesthetics of the context and reduce the perception of entering a space of different nature. For a better fulfilment of this requirement, the involvement of people taking part in the tests might be envisaged for better adjusting the interiors to their habits and activities.

5.2. Location and spatial constraints

Once the requirements have been defined it is necessary to refer them to spatial constraints in order to translate them into design solutions.

FIG.16. EC_house. Source: Energy center – Politecnico di Torino http://www.energycenter.polito.it/

OFFICE arises within Energy Center Initiative, and it will physically develop inside EC_house (**FIG.16**). The facility will be located on the ground floor of EC_house, hosting a broad, not partitioned space of about 8 m height – currently not targeted to a specific function – whose aim is housing laboratories and activities in collaboration with enterprises or research institutions. The space (**FIG.17**) develops longitudinally to the main direction of the building, along the portico leading to the main entrance on EC_house hall. The slot aimed at housing OFFICE covers an area about 7 m wide – from pillar to pillar, along the transparent façade – and 5.5 m deep. The full-height window delimiting one side of the slot it the closest to the portico's end, so the main entrance.

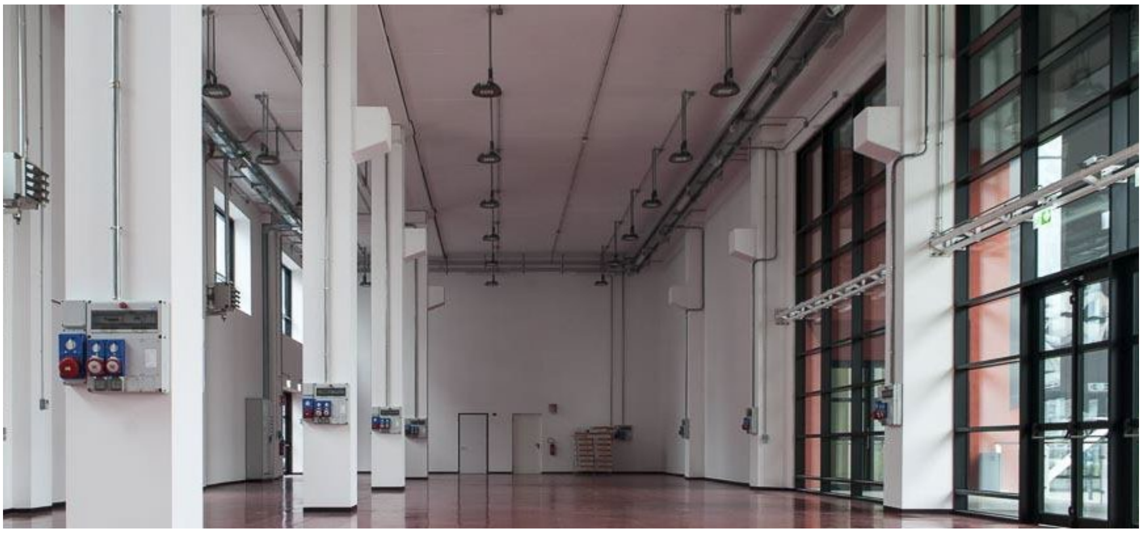

FIG.17. EC_house laboratory space. Source: Energy Center – Politecnico di Torino http://www.energycenter.polito.it/

Access to the laboratory area is provided through the transparent façade watching the portico (the doors location is shifted with respect to the area allocated to OFFICE project). At one end of the rectangular area there is access to a service zone, including restrooms and changing rooms: this feature suggests that a longitudinal, central distribution of the space will be provided and activities, including OFFICE, will develop at its sides. Consequently, the best side for accessing OFFICE facility seems to be opposite the transparent façade.

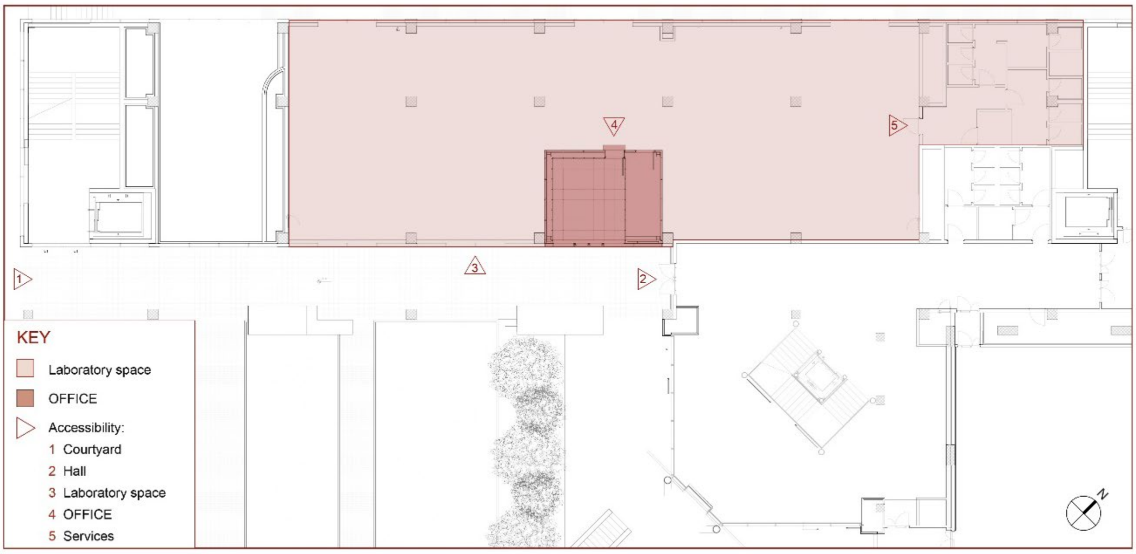

FIG.18. EC Lab ground floor plan.

The transparent façade faces the courtyard of the building and it is south-east oriented; however, because of the building configuration it is not exposed to full sun. In fact, it is shaded both by the projecting upper storey, and by the constructive elements wrapping the portico pillars.

5.3. Concept

OFFICE will be located in the laboratory space on the ground floor of EC_house whose function is currently undetermined, hence, the thermal conditions of the environment surrounding the facility are not defined. Moreover, because it is not being used, probably it is presently kept at a lower temperature than an occupied environment. As explained with reference to the controlled environment requirement, this factor makes OFFICE comparable to the outdoor test facilities described by Cattarin et al. (2016), which aim at minimizing thermal exchange through most of the sides for experimental purposes. OFFICE room will have a thermally insulated envelope and independent management of the technical building systems so as to ensure autonomy of the facility from the remaining part of the laboratory space. With reference to the research by Cattarin et al. (2016) the test room can be considered as a *guarded test cell*, that is an outdoor facility where “five of the six walls are not directly exposed to outdoor weather conditions but are surrounded by a thermally-controlled (guard) zone”. On one side, the provision of a guard zone will minimize the thermal exchange between test room and adjacent spaces, on the other side it will generate a gap for the placement, distribution and management of the technical building systems. This solution addresses and aims at satisfying different requirements, such as the creation of a controlled environment, the integration and distribution of the systems, and will allow to hide all the constructive and technical elements that would otherwise spoil the realistic features of the office environment. In a guarded test cell, the only façade directly exposed to outdoor weather conditions is the one thermal exchange is measured through. Considering OFFICE facility, the sixth wall corresponds to the transparent façade, whose modularity will be kept in order to allow the installation of different façade components and shading systems to be tested. Besides, modularity will characterize also the opaque walls, the floor and the ceiling delimiting the test room, so as to provide the expected setup flexibility, and facilitate the access to the gap for maintenance.

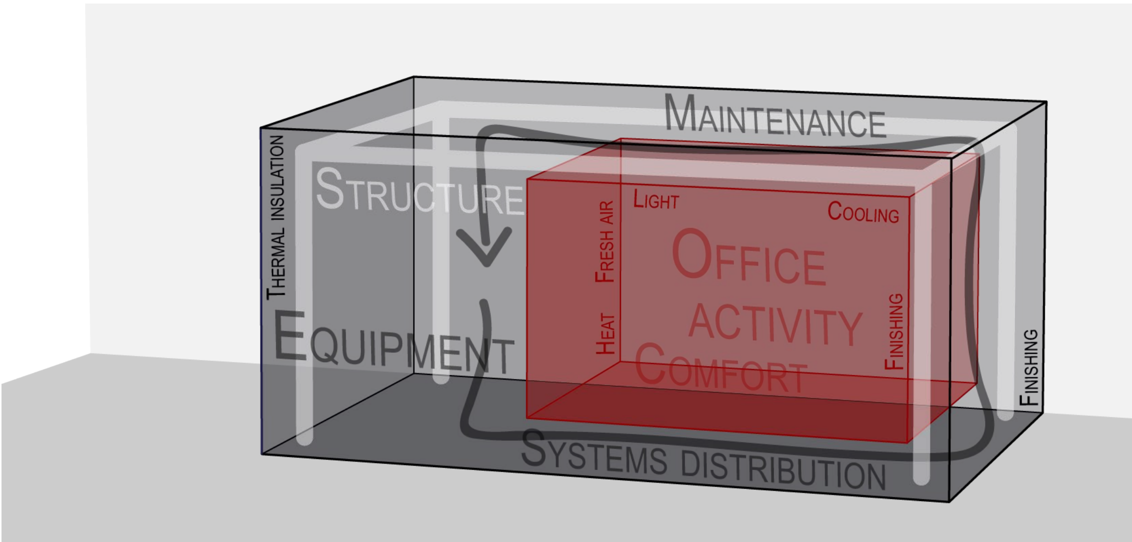

FIG.19. OFFICE facility as a shell within the shell.

According to the features described above it is possible to imagine OFFICE as a set of spaces defined by a shell within a shell (**FIG.19**), where: the core is a populated space where office activities take place and comfortable indoor conditions are supplied; the gap contains the load bearing structure and the technical building systems, and allows the presence of operators for the systems control, management and maintenance; the inner shell provides finishing, thermal insulation, and outputs of the technical building systems (light, heat, fresh air, etc.) to the core; the outer shell encloses the whole facility and reduces thermal exchange with the surrounding space.

5.4. Structure and materials

The requirements of setup flexibility, adaptability to future arrangements, and integrability of the instrumentation lead to the necessity of choosing building materials and technological solutions allowing reversibility such as dry construction and modular elements. Concerning the design of a realistic environment, the focus related to the material selection should take into account the features of interior characteristics of EC_house offices. Finally, due to the limited dimensions of the slot and the constraints related to building within an indoor space, the chosen elements should be slim, light, and easy to manage. The constructive elements presented in the following paragraphs address the requirements and constraints at the basis of the project and offer possible design solutions for the facility. The aspects presented are: load bearing structure, envelope (i.e. the walls, ceiling, and floor delimiting OFFICE within the laboratory space), transparent façade.

5.4.1. Load bearing structure

The facility will have a load bearing structure separate and independent with respect to that of EC_house. Lightweight solutions must be preferred because of the limited space; moreover, the load carried by the facility structure will be limited to the envelope because no upper floor is envisaged. Being used for sustaining a double layer of envelope, the inner and the outer shell, the optimal placement for the structure is in between them, in the gap described in the design concept, used also for the technical building systems distribution and management, and the thermal exchange control. As mentioned above, modularity will be one main feature of the constructive elements, therefore a dense, module-scale structure must be provided. However structural elements of bigger scale are required for transferring on the ground the load of the whole facility. Structural elements need to be lightweight to give as much space as possible to the systems distribution: steel structures represent a valuable solution in terms of resistance to the loads compared to their size. Concerning the facility-scale structure, the width (7 m) and depth (5.5 m) of the slot allow conceiving a pillar and beam structure with one single span in each direction, with the employment of steel profiles, for instance HE ones. The module-scale structure is meant for supporting the layers of materials constituting the envelope, described in the following paragraph.

According to the requirement analysis and the design concept formulation, the envelope is made of two shells separated by a gap where the thermal conditions are controlled, and the systems are placed. The same gap is the space where the structure is located. Considering the three opaque walls, both the inner and the outer shells should be anchored to metal-profile structures – running from pillar to pillar – where the span between the elements is determined by the modules dimension. The structure for elevating the floor is laid on the existing floor, while the supports for suspending the ceiling are anchored to a slab, which in turn is supported by the steel beams. According to the requirement of adaptability to future arrangements the slab should be preferably constructed following reversibility criteria and be suitable for the fixing of the suspended ceiling supports.

For instance, the use of steel decks in combination with prefabricated concrete-wood panels is a lightweight solution offering the necessary resistance in about 10-15 cm thickness and allowing re-use of the materials in case changes occur in the facility configuration and shape.

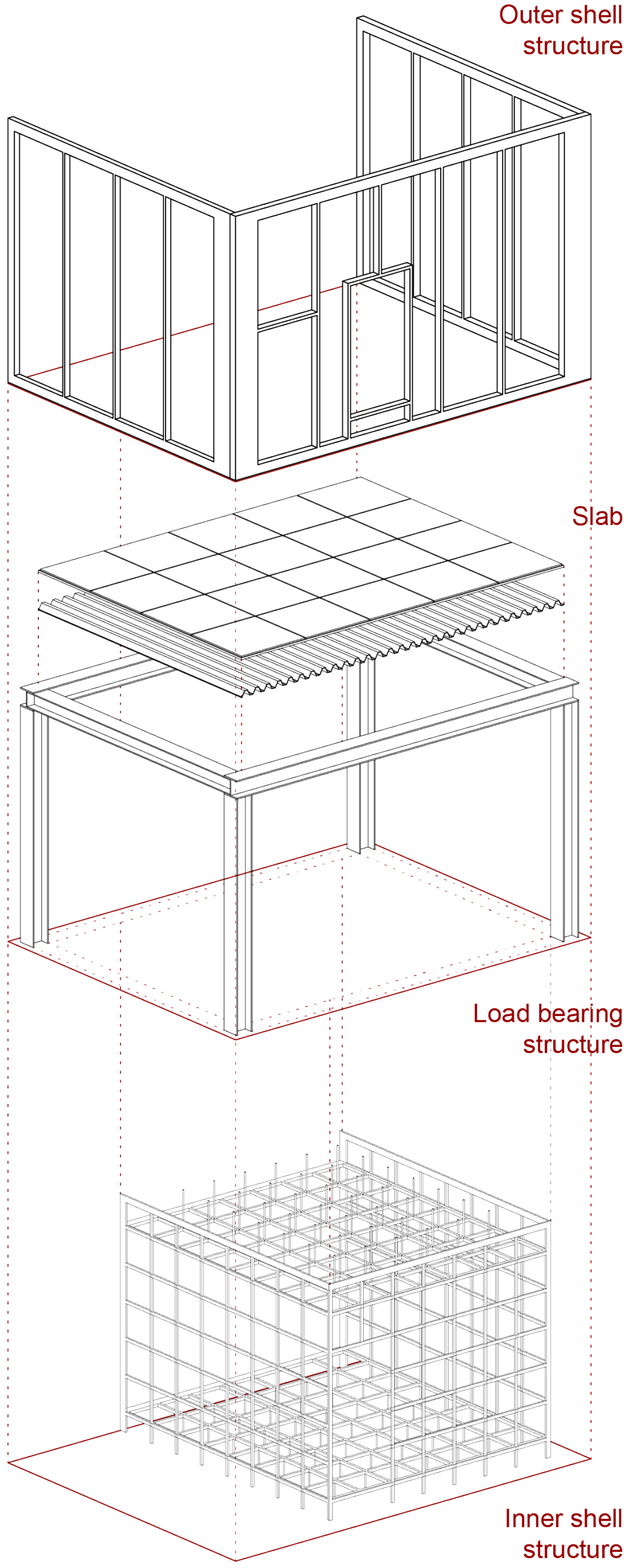

FIG.20. Exploded view of the bearing structure

5.4.2. Envelope

The envelope described in this paragraph it the one separating OFFICE room from the laboratory space on five of its six sides (the sixth side consists of the transparent façade analyzed in the following paragraph). This envelope consists of an inner and an outer shell separated by a gap having the function of a thermally controlled zone, and of a systems enclosure. The aim of the outer shell is enclosing the facility, providing thermal insulation, and give external finishing. Considering the three walls, they will include one or more layers of plasterboard (finished on the outside) and one layer of insulating material. On top of the room the outer shell consists of the slab described in the paragraph about the structure, together with thermal insulating material; on the bottom, instead, no outer shell is required since it is assumed the ground floor slab, where the facility is laid, is thermally insulated. The inner shell is the element where the need for modularity is stronger because of the setup flexibility requirement. A square modular shape with a 60 cm edge allows manageability of the elements and, in parallel, it keeps relatively low the number of elements needed for covering the entire facility walls. The same shape can be adopted for all the elements of the inner shell, so those in the walls, in the elevated floor, and in the suspended ceiling. The modules included in the initial design of OFFICE must respond to some essential requirements, such as mechanical resistance, durability, resistance to fire, etc. However, the employment of elements with higher performances (e.g. thermal insulating, low-polluting) or with additional features (e.g. including radiant system, light devices, air outlets, sensors, displays) is envisaged for the realization of different test scenarios. For this reason, the modules should be anchored to the supports through elements allowing

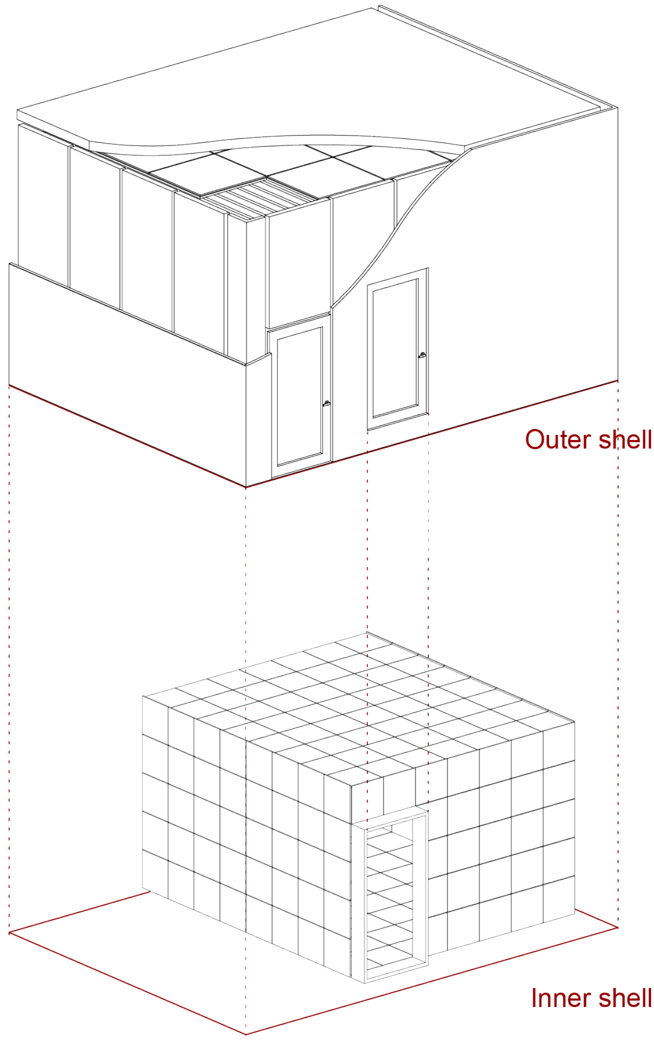

FIG.21. Exploded view of the envelope

easy removal. Because of the necessity to reproduce a realistic environment it is preferable the aesthetics of OFFICE interiors present similar features to those in the rest of EC_house. Most interior partitions in EC_house are white or transparent for maximizing the effectiveness of natural light. Consequently, for the inner shell of OFFICE white should be preferred. However, darker shades (for instance, in dark red tone, being red the tag color for EC_house) would be suitable as well for the floor modules; in an average office it is indeed easier to find a relatively dark floor and white walls.

5.4.3. Transparent façade.

OFFICE transparent façade is one of the elements which make the facility closer to a real office than to a laboratory, since it allows visual contact with the outdoors and with the people walking through the portico. Moreover, the full height window provides natural light that – besides offering the possibility to save electricity through a lower use of artificial lighting – has positive influence over the occupants' health and well-being. Nevertheless, the current state of the transparent façade adjacent to OFFICE slot does not allow natural ventilation, since it is made of fixed glass modules. The replacement of one module with operable windows is therefore necessary.

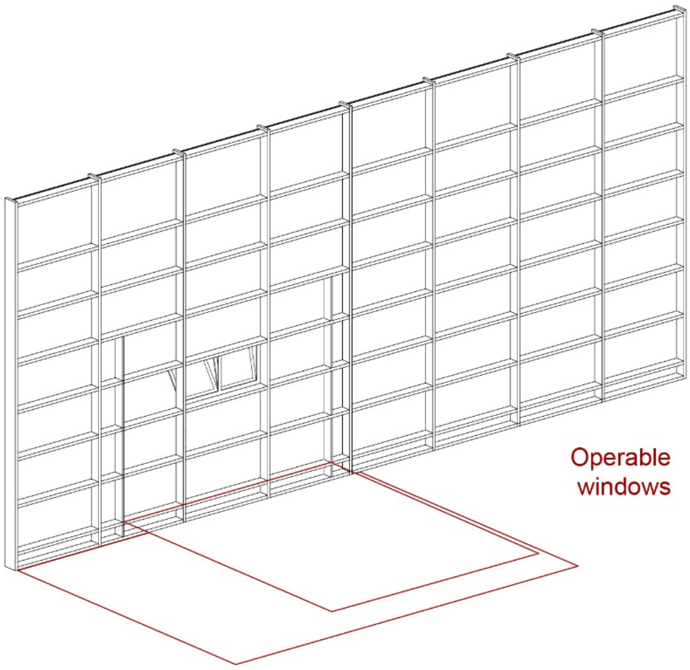

FIG.22A. Transparent facade

The inner shell of OFFICE environment covers a width of three glass modules and a height of four. The optimal positioning for operable windows is in the central module column because they would provide fresh air symmetrically, so affecting in the same way all workstations. The windows height should be chosen considering that OFFICE transparent façade faces the walkway to the main entrance of EC_house, therefore it would work better if kept above the head level of a standing person, so as to limit obstruction to the outside, voice noise and smoke intake to the inside. The windows showed in **FIG.22A** meets the requirements stated above and opening system conveys the fresh air towards the workstations. Replacing the modules would also allow the testing of the performance of transparent envelope elements. As explained previously, thanks to the thermally controlled zone, the facility allows monitoring the thermal exchange happening through the transparent wall, hence the performance of envelope elements. Conceptually, shading systems could be included as part of the dynamic envelope, but their usefulness should be evaluated subsequently to the analysis of the direct sun radiation the facility would receive. In fact, the portico is probably shading it for most of the sun hours. If it was proved that the presence of the portico actually influences the effects of the weather on the indoor climate, thus limiting the possibilities of test, a possible solution – that might be implemented according to the financial budget planned for the facility realization – would be making the indoor environment fully controlled, meaning that the guard zone would cover the transparent envelope of the facility as well as the opaque one. This is possible by means of the realization of a Double

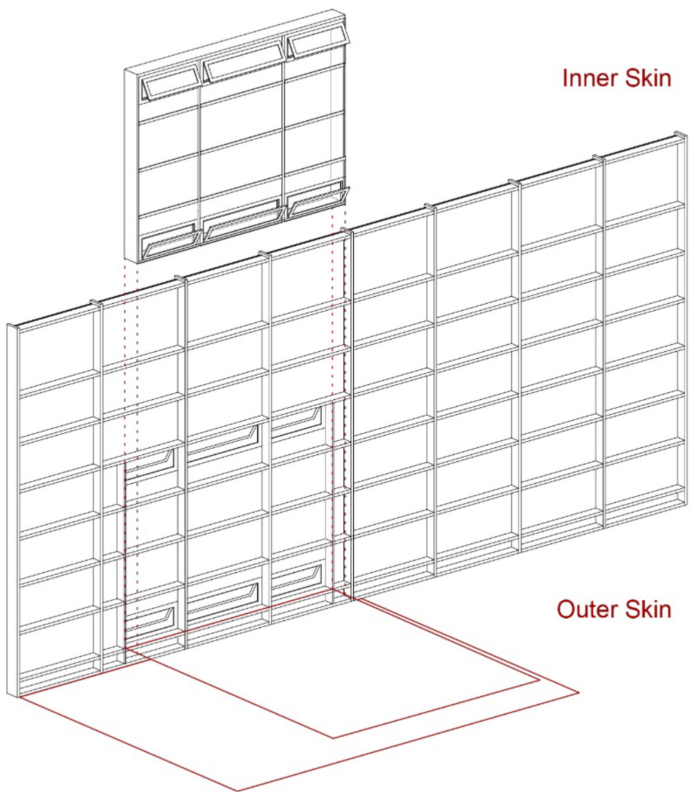

FIG.22B. Exploded view of the transparent façade with DSF

Skin Façade (DSF) where the climate in the gap between the two skins is controlled by means of air conditioning. Because it is used for simulating the outdoor climate the Double Skin Façade would not be connected to the guard zone, where the controlled climate reproduces an indoor one. In order to still allow natural ventilation, operable modules must be placed on both sides of the DSF. The configuration proposed in **FIG.22B** reproduces a solution described by Kalyanova and Heiselberg (2008), when presenting the "cube" facility. Besides the natural ventilation mode, the DSF in the "cube" can be employed as a *transparent insulation*, or an *external air curtain* (see **FIG.8**, Chapter 3). The first expression indicates the configuration in which all openings are closed and the DSF allows the heating of the air it contains through solar radiation, thus decreasing the heat loss through the transparent element; if solar radiation does not reach OFFICE façade, the air in the gap could be heated by means of air conditioning, so as to reproduce the effect of direct solar radiation. The second mode refers to the possibility of reducing the effects of solar heat gains by natural ventilation within the DSF, achievable by opening the windows on the outdoor side.

5.5. Space usability

This paragraph deals with the relation between OFFICE space and the occupants. Considering the dimensions of the available space for realizing the facility of 7 m x 5.5 m, and the need for creating a guard zone – about 0,5 m deep, for housing the load bearing structure and the systems – and a technical room – about 1,8 m deep, for placing machinery and devices, and allowing the their use and management by operators – it can be assumed the dimensions of the occupied office space will be about 4 m x 5 m. Those dimensions allow the positioning of four workstations, which should preferably be oriented with the side of the desks towards the windows, so as to avoid visual discomfort due to glare (direct or reflected on computer screens) and strong light contrast. According to the test scenario implemented, the optimal workstations disposition might vary. The room dimensions allow both a configuration where couples of desks lean on the lateral walls, and one where they face each other. Being the floor elevated, the room can be accessed through few steps or a ramp. Because of the assumptions on the distribution of the laboratory space displayed in paragraph 5.2, dealing with location and spatial constraints, the entrance door is located on the wall opposite to the transparent façade. Its position is shifted towards one corner, in order to leave space for some office furniture, or actuators of the technical building systems on the other side.

5.6. Fixed instrumentation

The goal of OFFICE tests is quantifying the energy savings with respect to the adoption of more or less automated control strategies, therefore, the facility must be firstly equipped with energy meters. Their use will be restricted to technicians and researchers;

occupants will receive energy consumption feedback through different interfaces. Therefore, energy meters will be located in the technical room. Other instrumentation will consist of sensory equipment used for measurements related to environmental conditions and occupant-building interaction, so it must be located in the test room. Data collection through sensors is fundamental for any kind of test scenario: both in case of manual adjustment and in case of automated technical building systems, it is necessary to have information about indoor (and even outdoor) conditions for implementing the proper adjustments. Hence, a set of sensors will be included in the fixed instrumentation of the laboratory, and all of them should be connected to a central system for data elaboration. Subsequently, according to the selected test scenario, adjustments of the technical building systems operation will depend either on the occupant action, or on an automated operation, therefore the actuators and technologies implemented should be fit case by case. Here comes the opportunity for local companies to promote the use of their own innovative technologies. These technologies might integrate sensors and actuators in one product (e.g. a thermostat with temperature and relative humidity sensors, a solar shade with light meter, etc.); in that case the parallel use of fixed sensors, selected for measuring with a high accuracy level, will give the opportunity to test the reliability of the sensors included in the products.

For monitoring the measurements and managing the automated TBS operation, an ICT system gathering information from all sensors and TBS, able to process them and present the results in an intuitive way, is required. Due to the variable setups that tests will assume, it is important to find a way to facilitate the programming of the sensors and TBS, for instance using visual-programming tools. One example of this kind is Node-RED, a flow-based tool developed by developed by IBM's Emerging Technology Services, which allows to gather and elaborate data coming from different sources – i.e. hardware devices, online services, etc. – by means of wires and boxes (or nodes). The latter either represent collections of data or functions for transforming the data; the nodes are wired together in logical order for obtaining the data transformation required. Because of the intuitive programming interface, a tool of this kind seems to fit the setup flexibility required for OFFICE.

Details on the measured parameters and the employed sensory equipment, with specification about their disposition and other features, is provided in the following paragraphs; that information is then summarized in **TAB.3**. The parameters planned to be evaluated in OFFICE are finally compared to those measured in the reviewed facilities in **TAB.4**. This comparison table is meant as a tool to be used in future steps of OFFICE project, and it aims at facilitating the search for information within the reviewed literature, about the measurement of specific variables.

5.6.1. Thermal comfort: temperature, relative humidity and air velocity

In most of the facilities for indoor environmental tests the operative temperature is measured. It is a parameter which considers the effects of both convective and radiant heat transfer. In experiments carried out in LOBSTER (Schweiker and Wagner, 2016) operative temperature calculation was based on air temperature, globe temperature and air velocity, which were measured adjacent to the workplaces and close to the middle of the room. The sensory equipment required for the measurements consists in a temperature sensor (e.g. a resistance temperature detector), a black-globe thermometer, and an anemometer; according to the reviewed experiments they might be located at a height between 60 cm and 110 cm. For the temperature sensor a height of 110 cm, corresponding to the head level of a sitting person, should be preferred. In fact, if a further temperature sensor is positioned at the feet level – 10 cm – the vertical temperature gradient between head and feet level can be monitored. Standard ISO 7730:2005(E) sets, indeed, high vertical air temperature difference between head and ankles as a possible cause of thermal discomfort. The described instrumentation could be fixed on a mobile support so as to be placed in the most convenient position according to the room spatial configuration (**FIG.23A**). Alternatively, the support could be integrated in the workstation (**FIG.23B**), but this solution would work properly only in case the workstations are located in the middle of the room and heat emitting devices (e.g. computers, table lamps, etc.) are be kept at suitable distance from the sensory equipment, not to invalidate the measurements.

As mentioned above, the globe temperature is used for calculating the operative temperature. This is because it is a parameter used for the mean radiant temperature calculation, which is used in turn in the formula for calculating the operative temperature. However, there is an alternative way for calculating the mean radiant temperature, which requires the measurement of the temperatures on the surfaces delimiting the room (walls, floor, ceiling). Therefore, more temperature sensors might be positioned on those surfaces, for instance they might be integrated in special inner envelope modules, thus giving the opportunity of a double check on mean radiant temperature measurements.

Together with temperature and air velocity, relative humidity is another parameter influencing thermal comfort. For measuring it a hygrometer should be located close to the workstation and in the central area of the room, therefore the same support used for the measurements described above could be employed (**FIG.23A** and **B**).

The measurements related to thermal comfort are meant for regulating the operation of the TBS of heating, cooling and controlled ventilation.

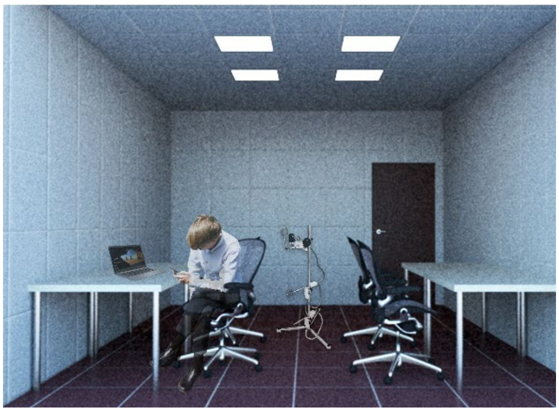

FIG.23A. The workstations are leaning against the walls; the sensors are fixed on a mobile support in the central area of the room. It is a flexible solution, but the support may obstruct the way between entrance and workstations.

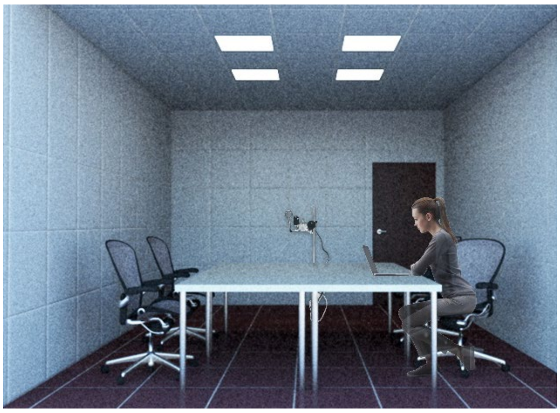

FIG.23B. The workstations are gathered in the middle of the room; the sensors are fixed on a support integrated to a desk. This solution is convenient in terms of accessibility to the workstations, but occupants should pay attention not to keep devices (e.g. laptops) too close to the sensors.

5.6.2. Visual comfort: illuminance

In an office environment where occupants spend all day working at a desk it is important to make sure the proper amount of light on the horizontal work plan is provided. For this reason, illuminance will be measured relatively to each workstation through light meters positioned on the desks.

The measurement of the illuminance is meant for regulating the operation of the TBS of lighting and dynamic building envelope.

5.6.3. Air quality: CO_2 and VOC concentration

A high concentration of CO_2 and Volatile Organic Compound (VOC) in an indoor environment causes problems of concentration and symptoms related to the Sick Building Syndrome. Sensors for measuring CO_2 and VOC concentration should be located at the head level of occupants and in the central area of the room so as to keep the same distance from each workstation.

The measurement of air quality parameters is meant for regulating the operation of the TBS of controlled ventilation and dynamic building envelope.

5.6.4. Indoor/outdoor environment interaction

The transparent façade of OFFICE facility constitutes a direct connection to the outdoors in terms of thermal exchange, natural light transmission, and view. Considering thermal and lighting aspects, monitoring outdoor parameters (air temperature, relative humidity, global solar radiation, etc.) allows a better control of the interaction between indoor and outdoor conditions; for this reason, a proper location in the courtyard will be individuated for installing a weather station. In presence of operable windows, the influence of outdoor conditions on the indoor environment does change according to the state of the openings, that is whether they are open or closed: contact sensors will be provided for detecting their state. Being the façade to the outdoors subject to variations due to the test of different envelope elements, the number of sensors needed will vary according to the number of operable windows. In case a DSF system is implemented, temperature and relative humidity measurements will be performed in the cavity between the two transparent skins and controlled by means of air conditioning for simulating outdoor conditions tailored case by case.

The measurement of outdoor environmental parameters and window state is meant for regulating the operation of the TBS of dynamic building envelope, lighting, heating, cooling and controlled ventilation.

5.6.5. Occupancy

Indoor and outdoor environmental parameters are needed in order to provide the best indoor conditions to the occupants while saving as much energy as possible. However, the TBS adjustment should also consider the occupancy of the room, i.e. if occupants are present in the room, and if so, which workstation are they using. Hence, an occupancy sensor – for example a Passive Infrared (PIR) sensor – will be fixed to the central area of the ceiling for detecting the presence of people in the room. Besides, temperature sensors might be fixed to each workstation, as close as possible to the seat, for measuring sudden temperature variations, meaning that a person has reached or left the workstation. In this way, the workstation devices could be switched on/off according to the presence or absence of a person.

The occupancy detection is meant for regulating the operation of all TBS. Moreover, the effectiveness of the adjustments could be enhanced by recording the occupancy patterns, thus allowing predictive operation of the TBS.

Parameter	Instrument	Positioning
Energy	Energy meters	Technical room
Air temperature	Temperature detectors	Test room: • Central area, 110 cm height • Central area, 10 cm height • On each desk, close to the seat
Surface temperature	Temperature detectors	Test room: • On floor, ceiling, opaque walls, transparent wall, in the center of each surface
Globe temperature	Black-globe thermometer	Test room: • Central area, 60 to 110 cm height
Air velocity	Anemometer	Test room: • Central area, 60 to 110 cm height
Relative Humidity	Hygrometer	Test room: • Central area, 60 to 110 cm height
Illuminance	Lightmeter	Test room: • One sensor on each desk
CO_2 concentration	CO_2 sensor (e.g. Infrared)	Test room: • Central area, 110 cm height
VOC concentration	VOC sensor	Test room: • Central area, 110 cm height
Outdoor environment	Weather station	Courtyard
Occupancy	Occupancy detector (e.g. PIR sensor)	Test room: • Ceiling mount, center of the surface

TAB.3. Summary table of the fixed instrumentation provided in OFFICE.

FACILITIES								MEASURED VARIABLES															
General information			Test objectives					Temperature			Relative Humidity		Air flow		Air Quality		Light	Dynamic envelope		Physiology		Heat	
Name	Location	Date of construction	Thermal comfort	Visual comfort	Air quality	Energy consumption	Occupant behavior	Indoor air	Operative (indoor)	Outdoor air	Indoor	Outdoor	Air velocity	Air exchange rate	CO2 concentration	VOC concentration	Illuminance	Window open/closed	Shading system position	Skin temperature	Heart Rate	Solar heat gains	Internal loads
ICIEE	DTU, Denmark																						
Climate chambers		1972 on	●				●	●	●	●	●	●	●	nf	nf	nf	nf			●	●	o	nf
Field laboratories		2001 on	●		●		●	●	●	●	●	●	●	●	●	●	●	nf	nf	●	●	nf	nf
CEC	UC Berkeley, USA	1988	●		●	●	●	●	nf	●	●	●	●	●	nf	nf	nf	nf	nf	●	nf	nf	●
IEQ Lab	University of Sidney, Australia	2012	●	●		●	●	●	nf	●	●	nf	●	nf	●	●	●	nf	nf	●	●	nf	nf
LOBSTER	KIT, Germany	2013	●				●	●	●	●	●	●	●	nf	nf	nf	nf	●	●	nf	nf	●	nf
CREATE Tower - SinBerBEST Test Bed	University Town, Singapore	nf	●	●	●			●	nf	●	●	●	nf	nf	●	nf	●			nf	nf	nf	nf
E.ON Energy Research Center	RWTH Aachen University, Germany	nf	●	●	●			●	nf	nf	●	nf	nf	nf	●	●	nf	nf	nf	nf	nf	nf	nf
Indoor Env. Labs	Fraunhofer IBP, Germany	nf																					
HiPIE-Lab, IATC			●	●	●			●	nf	nf	nf	nf	nf	nf	●	●	●	nf	nf	nf	nf	nf	nf
VERU			●	●	●	●		●	nf	nf	●	nf	nf	nf	nf	nf	●	nf	nf	nf	nf	●	nf
OFFICE	Energy Center, Politecnico di Torino, Italy	-				●	●	●	●	●	●	●	●		●	●	●	●					

Key: ● = present feature | nf = not found information about this feature

TAB.4. Comparison between the measurements performed in the reviewed facilities and those planned for OFFICE.

6. Conclusions

The global environmental situation of the present time has proved that the *control* of e*nergy-efficiency* in our everyday energy-consuming activities is among the enablers of a sustainable future. On one side, technologies and strategies *innovation* must be *fostered*; on the other side, it is necessary to make sure that *users* are aware of the ongoing transition, and innovative solutions are *tailored* for them. This is why OFFICE, the new *facility* by EC_lab, aims at enclosing – even in its acronym – the key issues of the present international energy research panorama.

Within OFFICE initiative, the study presented in this dissertation plays the role of a forerunner, a preliminary investigation of the project framework and of the opportunities it offers. The prime contribution of this work is identifying the architectural requirements and potential design solutions for the facility. A similar activity needs to be performed with respect to the engineering of the Technical Building Systems, and the planning of the ICT to be employed in the facility. A multi-disciplinary approach is, indeed, a key aspect in the pursuit of smartness, a capability which can be reached only if all the parts of a system – being it a building, an energy grid, or a city – are able to communicate and optimize the combination of their operation according to the present needs. Once the preliminary design of OFFICE facility is complete, and it is ensured the different aspects are well integrated, the concerned actors shall start the planning of the activity and set up a competition for the actual realization of the facility.

The existing facilities, the projects, the research issues and the international policies reviewed within this dissertation constitute a fundamental contribution to the draft design presented in Chapter 5. However, the collected information – in particular the parts concerning facilities and ongoing projects – could be considered as a reference for the coming steps of OFFICE, or even a starting point for deepening the research and keeping the review updated. Strength and weaknesses of other research experiences could be a boost towards effective solutions.

The requirements – both those identified in the previous chapter and possible new ones – should be acknowledged during all the phases of project planning and realization. For instance, the adaptability to future arrangements could be a crucial feature for partnerships: the collaboration with some enterprises might allow greater economic availability, thus the realization of a larger facility together with the increase of research opportunities. The requirement of a controlled environment has been tackled only partly in this dissertation because it has its main implications with respect to the planning of TBS and ICT solutions; their integration with the architectural design solutions might entail the adjustment of the latter. Instrumentation integrability and flexible setup are most influential in the choice of the constructive elements. As explained in the previous chapters, the facility should include a basic equipment of envelope elements, possibly integrated sensors, and TBS terminations; nevertheless, some alternative solutions could be envisaged as part of this basic equipment, for instance different set of modules (varying in material, properties, etc.) could be provided for the inner shell. It is finally worth mentioning the role of the occupant with respect to the realization of a realistic environment. Hitherto this requirement has been considered in general terms of liveability of an indoor environment; however, in order to actually tailor the facility, the users occupying it should be identified. For avoiding bias in the tests results subjects who are neutral with respect to the project – which means they should get some information about the research goals, but they should not know how the test works – shall be preferred. Hence their working habits should be investigated, and their usual working environment explored, so as to adjusting the indoor space according to their needs and preferences. After all, if comfort and wellbeing are among the main goals of smartness in buildings, dealing with occupants' involvement and awareness is a necessary step for meeting the target.

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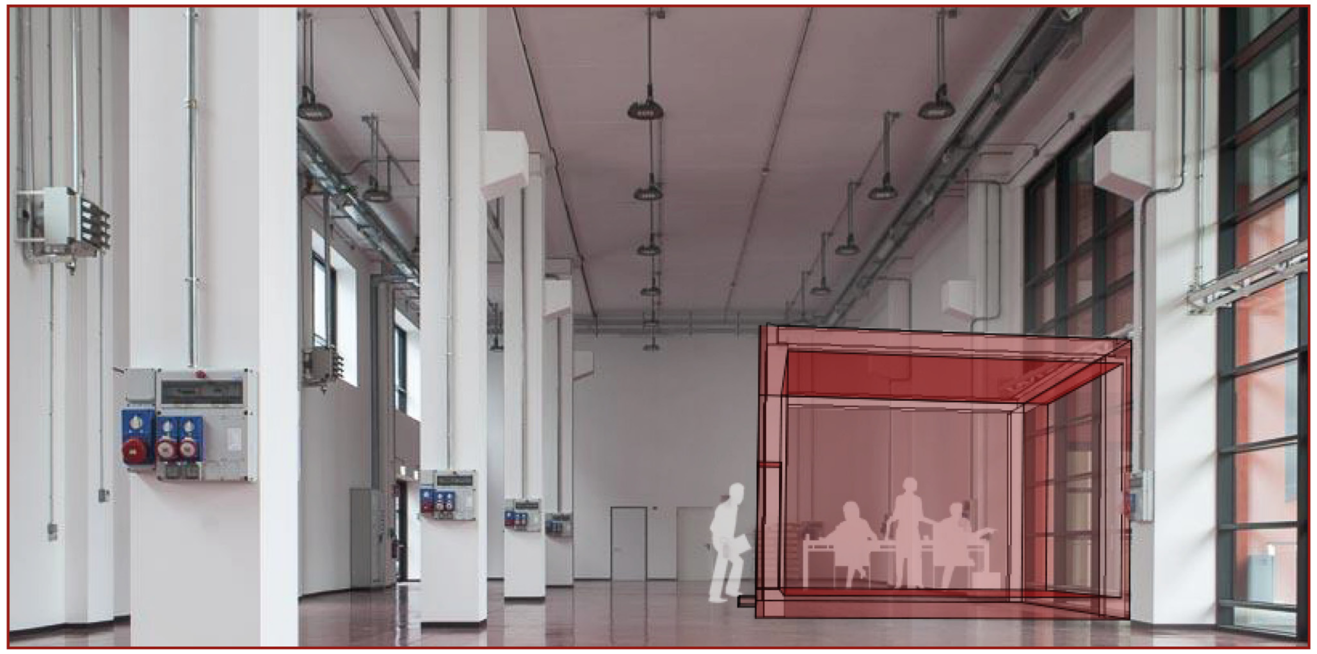
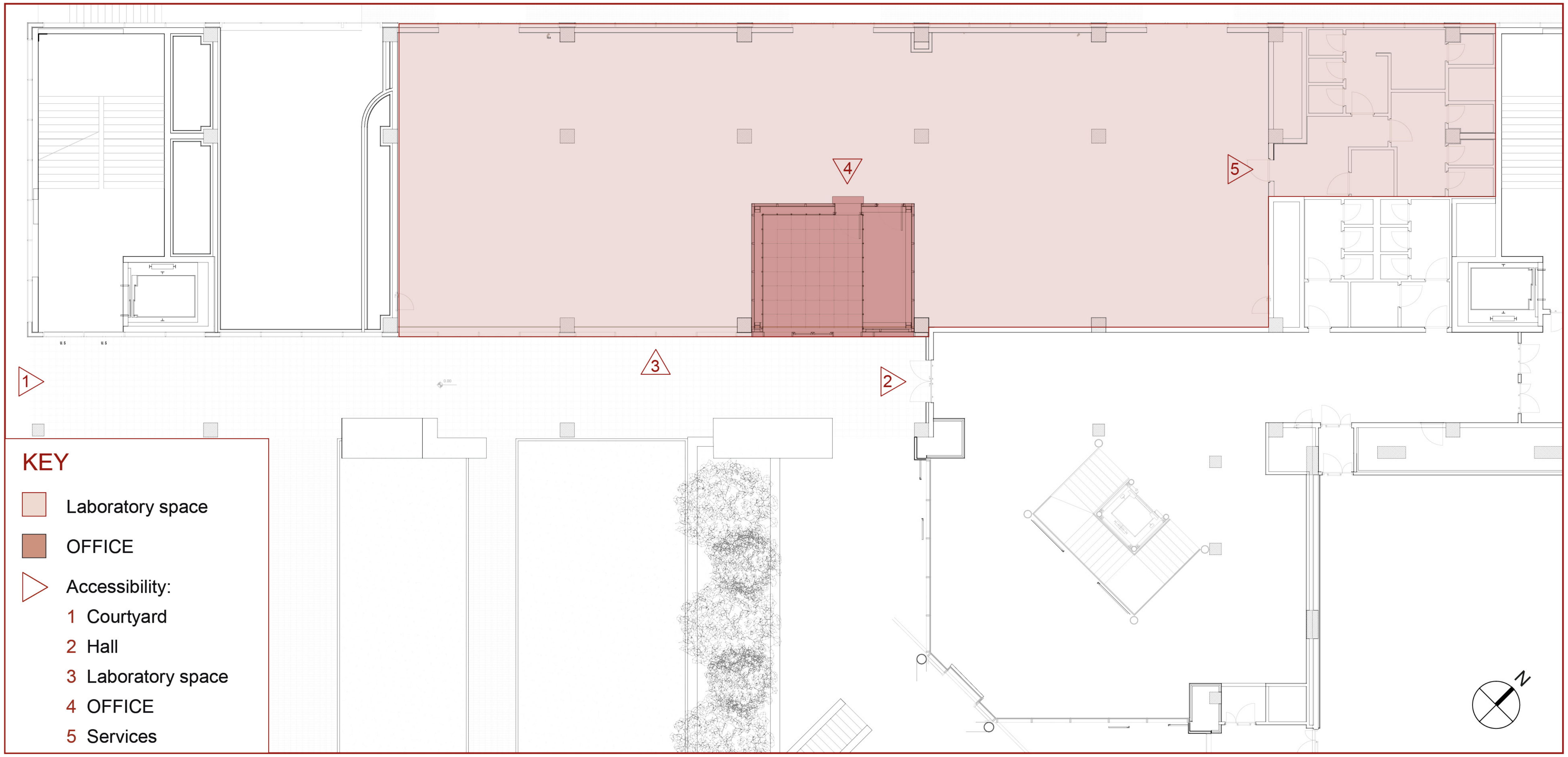
Appendix

EC_house south view



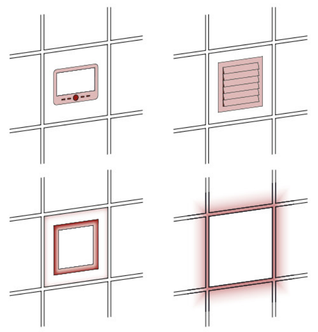
Laboratory space hosting OFFICE



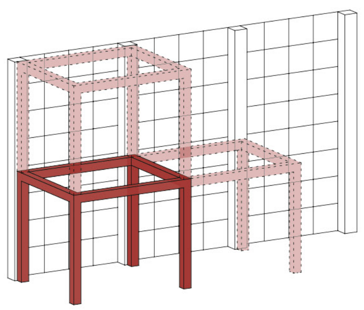
EC_house grand floor plan (1:200)

OCCUPANT-TAILORED FACILITY FOSTERING INNOVATION IN CONTROLLING ENERGY-EFFICIENCY

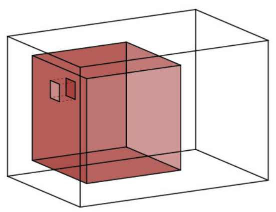
FLEXIBLE SETUP



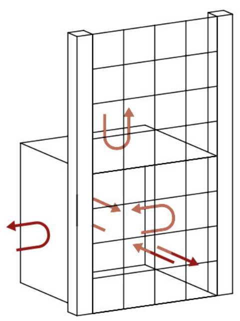
ADAPTABLE SPACE



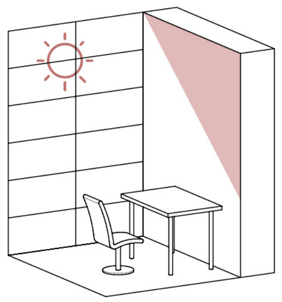
INTEGRATED SERVICES



CONTROLLED ENVIRONMENT

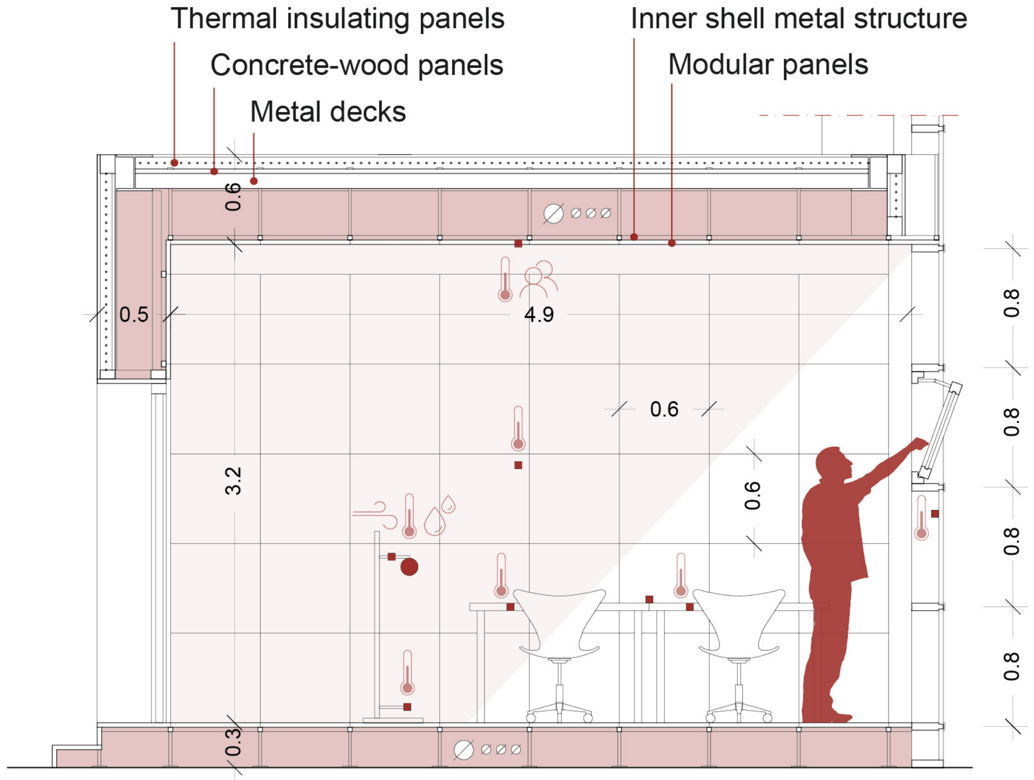


REALISTIC OFFICE



Facility design

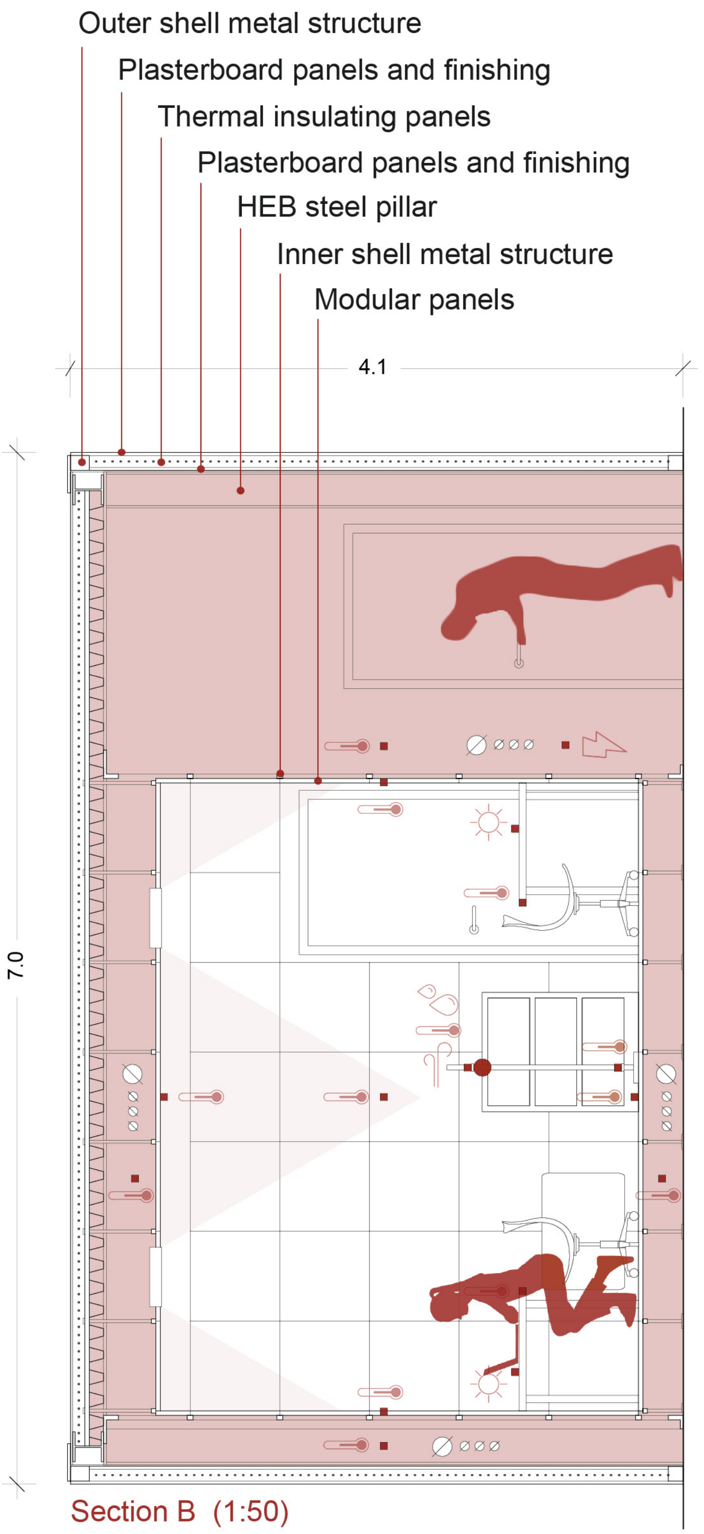
The test room is set up as a realistic office environment. On five envelope sides it is surrounded by a guard zone allowing thermal control and services flexibility. The transparent façade to the outside can be used for envelope elements testing. In the facility setup presented here, it is equipped with operable windows.



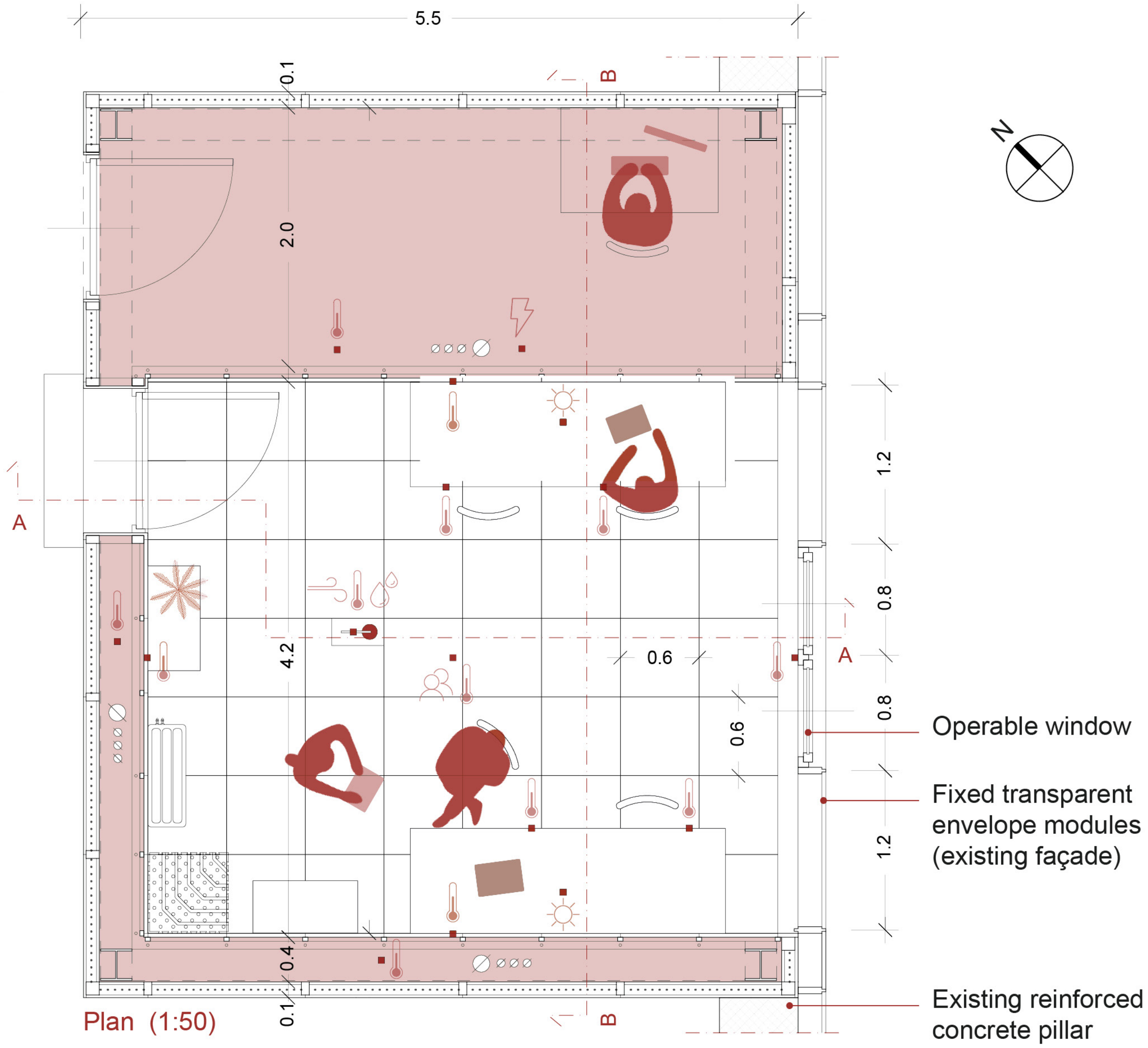
Section A (1:50)

SENSORS

- Air / surface temperature
- Globe temperature
- Relative humidity
- Air velocity
- Daylight
- Occupancy
- Energy meters



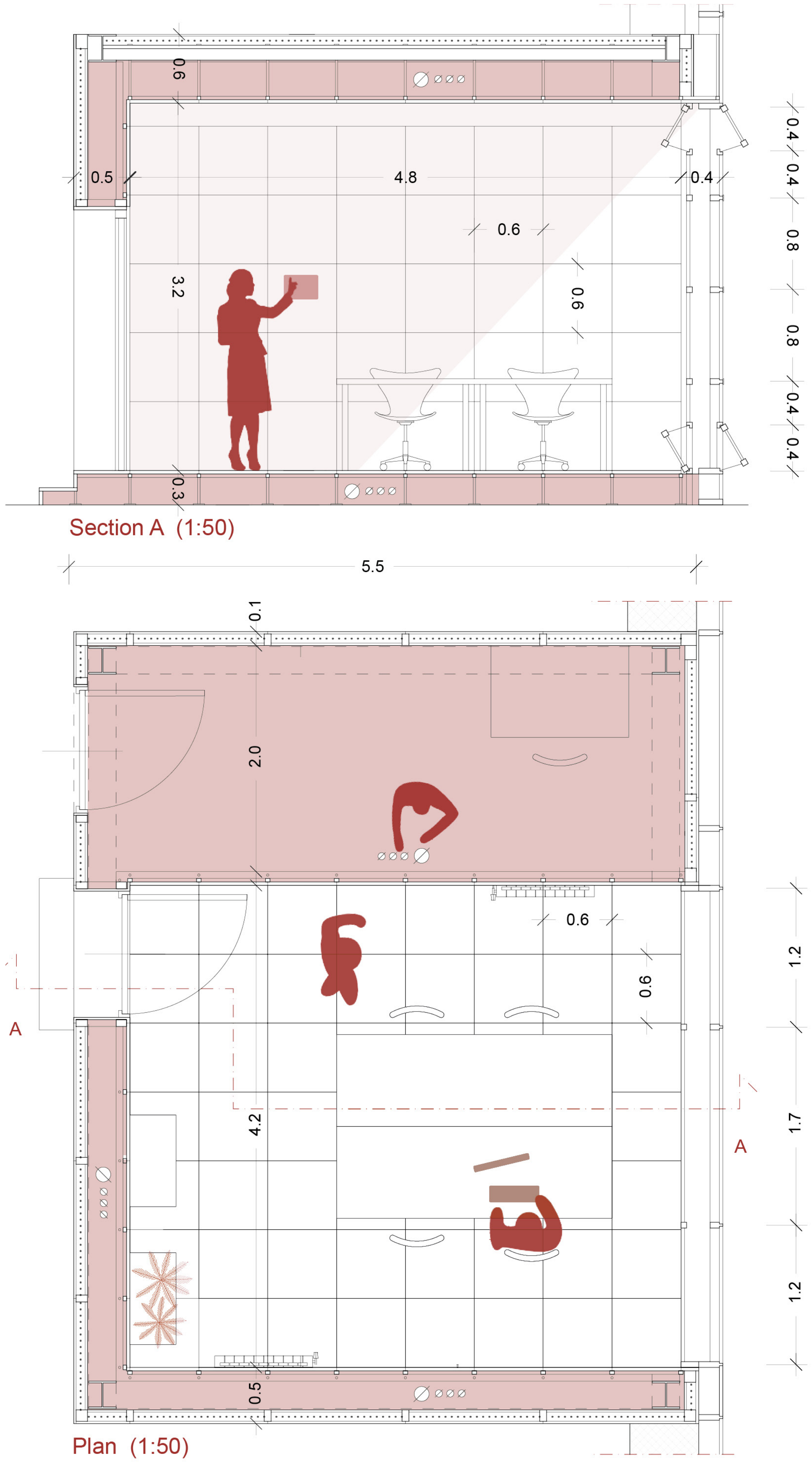
Section B (1:50)



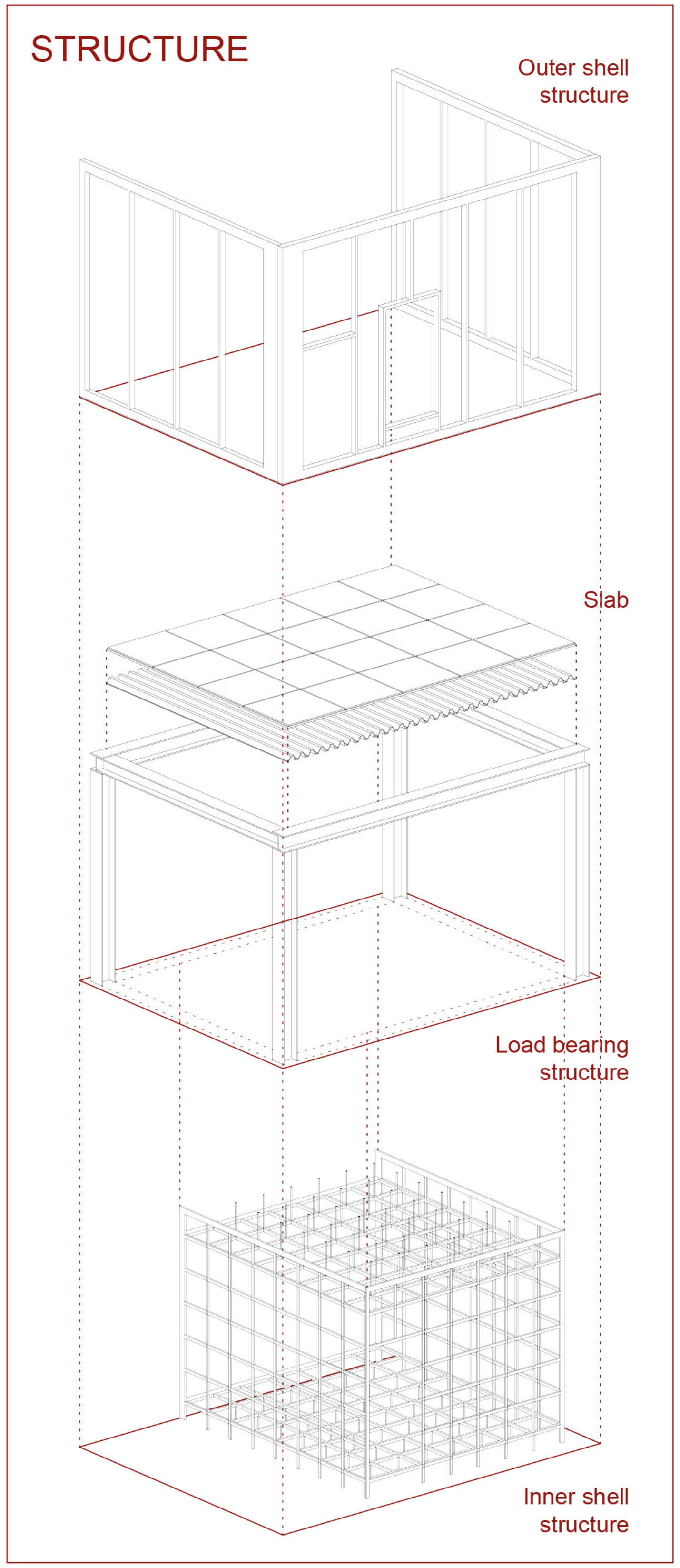
Plan (1:50)

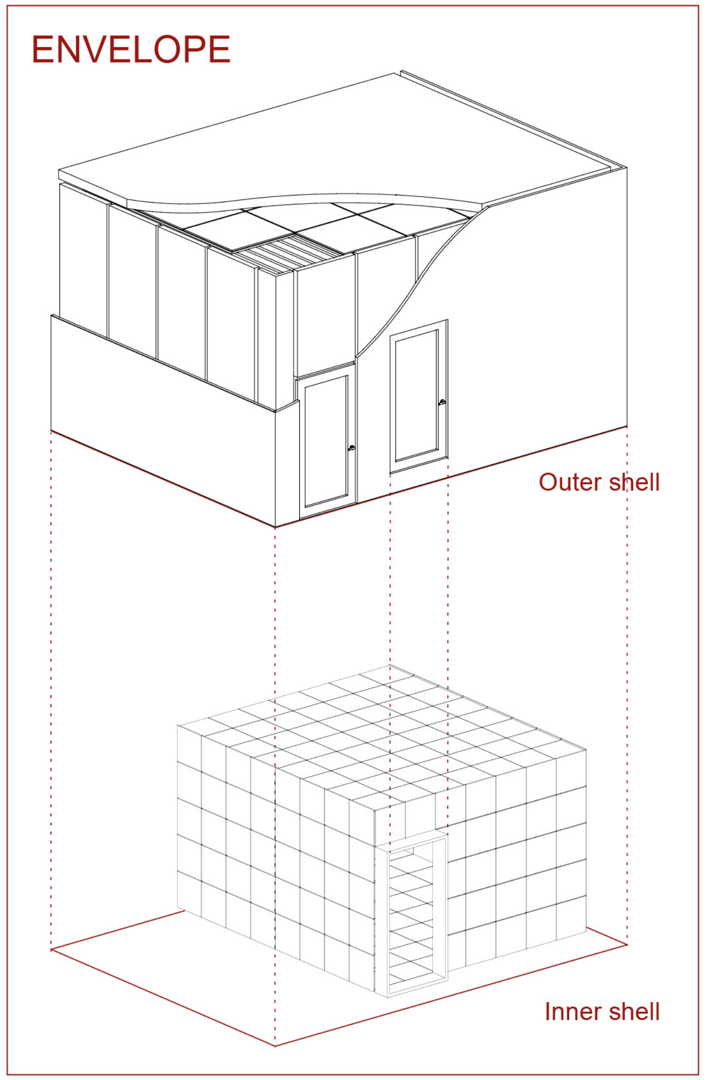
OCCUPANT-TAILORED FACILITY FOSTERING INNOVATION IN CONTROLLING ENERGY-EFFICIENCY

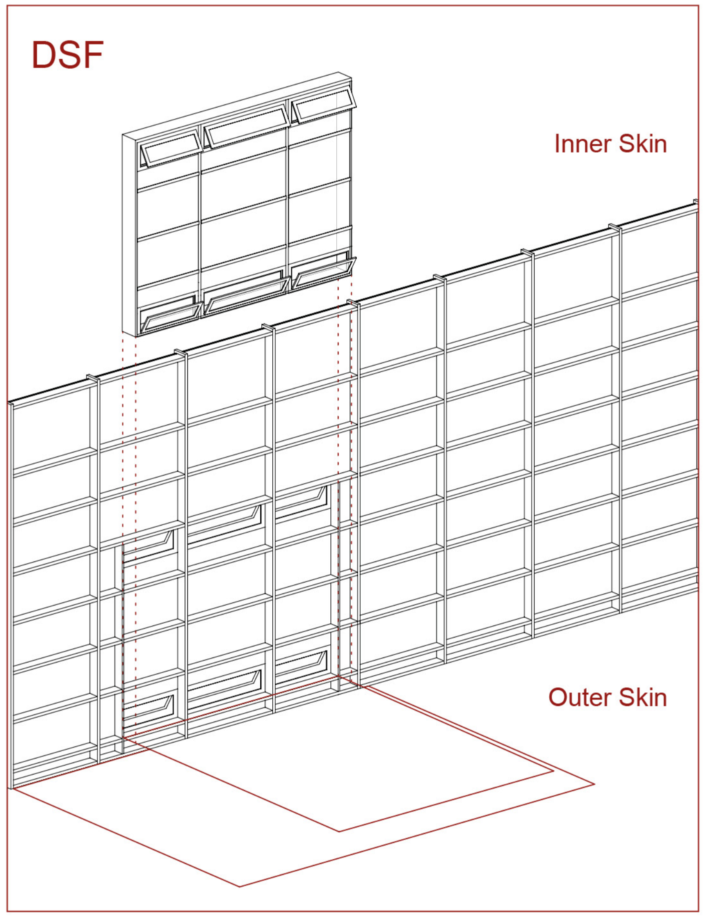
Constituent parts and design of a Double Skin Façade



A transparent Double Skin Façade (DSF) would constitute an additional guard zone on the sixth side, i.e. the transparent envelope. The thermal conditions within the DSF would be controlled independently from those in the opaque guard zone to allow the simulation of outdoor conditions.







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