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TOWARDS A NEW ETHICS IN BUILDING

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EDITORIAL
TOWARDS A NEW ETHICS IN BUILDING

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Crises, which are overwhelmingly destabilizing the most established references with increasing frequency, are no more situational but systemic: therefore, responses to these crises require actual paradigm shifts. This assumption, as a non-casual coincidence with the 50th anniversary of the publication of the founding text *The limits to growth*, moved the Journal TEMA to launch this call for papers: *Towards a New Ethics in Building*. Thus, the goal was to capture the features and implications of paradigm shifts and transfer them to our research and scientific interest areas. This process has been accomplished both through *overviews*, helping to grasp the main relational and systemic aspects and *insights* into operational tools and methods and case studies specifically related to the built environment. This organization of essays is effectively reflected in the manuscripts that compose the presented thematic issue.

The three-year period 2019-2021 was not only the *bearer of global crises* but also, fortunately, a pivotal moment of responses at the level of top political-institutional decision-makers. In fact, contextually, Europe led a great project, at once political and socio-economic, namely the *Green Deal*, intending to transfer knowledge, proposals and solutions on the level of major strategic projects. The scientific-technological area of the *building sector*, in particular, immediately recognized itself in the *Renovation Wave Strategy Directive* (14.10.2020). For the first time, after decades of directives dedicated to issues of enormous impact (i.e., transport, energy, environment, etc.), nonetheless still conceived in a sectoral way, the issues of the *built environment* were being prioritized. More importantly, strategies were also being institutionally placed at the proper level of complexity. It was a matter of converging green goals in the city, construction and performance (according to a *circular approach*) with social cohesion and new welfare, having the quality of life and work as the main content and goal. Indeed, the three keywords of the Directive are: *greening our buildings*, *creating jobs*, and *improving lives*. Certainly, on the application level, inconsistencies and contradictions have already manifested themselves; the Italian NRRP (National Recovery and Resilience Plan), for example, with its bonuses, has so far failed to be up to the premises. However, at least on the level of legitimacy and support for a set of new theoretical and practical experiments, the *Green Deal* and *Renovation Wave* seem to have already actually made their mark. The research has taken note of the shift that the ethical dimension entails: an increasingly intersectoral/multidimensional approach, a growing contamination between society and science, and an orientation of the latter to seek responses more and more oriented to emerging social and environmental needs.

In its opening, this issue presents three introductory essays, constituting three broad *overviews*. The authors all pertain to the field that we can still call polytechnic, i.e., Engineering and Architecture, although they belong to different areas, sectors, and generations, and above all being bearers of seemingly distant cultures and research profiles. For this reason, too, reading the different declinations and emphases on principles, the different narrative styles with which they illustrate their theses and viewpoints on the *paradigm shift*, gives a grasp of the value of the differences but also the (wholly unplanned) mutual cross-references and many substantial and significant convergences.

In the first essay, *The ecological transition of cities*, the author, emeritus professor Federico M. Butera, widely known for his committed call to *deal with complexity* while identifying cities as the core of the problem and also the solution, poses the question in terms of urban and environmental metabolism. The use of the term and the concept of urban metabolism itself goes far beyond the metaphorical dimension and becomes a pregnant analogy between systemic entities (i.e., eco-biosphere superorganism and urban or territorial organism). Entities in which flows of matter and energy realize complex dynamics affecting and continually modifying the initial systemic arrangements. These modifications, however, have come to be measured by an ecosystem in which there is no longer an *elsewhere* in which to converge waste. It is worth noting how China has become the world's true manufacturer and how yet still the emissions that come from factories located in China's territory are almost always blamed on China itself, which, nevertheless, operates in the service of that great global city, that is the European and North American West. Butera clarifies that this is not merely a matter of accounting and production. Consumption is influenced, mainly and above all, by *lifestyles* and related social status, without taking into account that even virtuous actions, such as energy efficiency in buildings, can produce counterintuitive outcomes. Against a reductionist view and the underlying *purely linear* logic, whereby problems are addressed and solved more efficiently by optimizing emerging sectoral aspects, for Butera, it is a matter of designing the future adaptively as a complex and largely unpredictable ecosystem.

In the essay *Environmental ethics and sustainability of techniques. From hyper-specialization to multifunctionality for a resilient inhabitable space*, Mario Losasso recalls the human-nature unity, reminding the reader as the techniques and productive and social arrangements that result from them are also part of the overall ecosystem. The new environmental ethic consists precisely of the critique of a model based on the domination of nature by a *rational-to-the-purpose* technique, which is contrasted with a co-evolutionary vision. Through this, human communities are called to develop neo-ecosystems of which they recognize themselves as an integral part: thus, they do not have a position of passive protection but a role in the regenerative co-design. This position invokes the theme of city and settlement life as an evolved form of metabolism. The organicist metaphor means that much of the investment in the human habitat of the future will consist of a regeneration of the existing building stock aimed at converting the current linear production-consumption-waste sequence into circular procedures with minimal waste, as the *Renovation Wave Strategy* states. This vision is equivalent to saying that the project must structurally place itself in terms of *ecosystem reactivation* by introducing the operational category of habitable/livable space, referring to the fruitful research of the 1960s and 1970s. Munari, Maldonado, and Vittoria, among others, in that historical passage, posed to architecture and technology the question of how to rethink and design habitable space in symbiotic terms and not in terms of resource exploitation. A concept already half a century ago pointed to a multifunctional alternative to sectoral hyper-specialization.

In the third essay, *Innovation and knowledge-based growth for two low carbon transitions in the built environment. Challenges and open research questions*, Massimiliano Manfren moves from similar premises:

- radical innovation (corresponding to the paradigm shift horizon);
- decoupling of social and economic growth from resource consumption (sufficiency);
- decided orientation toward complex and interscalar approaches;
- centrality of social and cultural factors over the reductionist hyper technological approach.

The author interprets them by placing the topics first and foremost from the knowledge-based development perspective (knowledge-based growth perspective). Of this perspective, meanwhile, the essay examines the complex relationships between technological innovation and policy directions because of the decisive role that decisive issues of a deeply social and cultural nature, such as lifestyles and consumption patterns, play with respect to the ultimate goal of minimizing global emissions. For the author, *sufficiency* in transforming the circular economy into behavior opens a relevant perspective to new trades for new forms of space use in a multifunctional and shared approach. Equally relevant is the critical argument about the risk of *wishful thinking* about replacing obsolete and increasingly marginal jobs with more skilled activities that constitute the new and more fulfilling factor of social cohesion. Sharply identified are the structural constraints to the emergence of types of innovation diffusion that do not result, as is increasingly the case, in expanded inequality and exclusion. Moreover, it is pointed out that the new goal of the *knowledge economy* seems to have been decisively downsized: no longer the increase in the number of employed people, but at least the non-reduction compared to traditional jobs. Only mass co-interest in the challenge of sustainable innovation creates the social cohesion required to avoid disaffection with democracy. New innovation ecosystems must therefore be fostered and supported in public and corporate governance, and decision-making processes should be supported by data-driven procedures defined by the use of Artificial Intelligence (AI) and Machine Learning (ML) applied to building-generated big data. In conclusion, the author asks crucial research questions: Is the human dimension considered and properly accounted for? (e.g., all aspects related to behavioral change, which can, directly and indirectly, impact carbon emissions)? In this regard, it would be essential and urgent for a review of Italian policies related to the 110% bonus to ask the question and answer it correctly.

The pandemic has overwhelmingly brought out a new social demand for quality of life in inhabited spaces, highlighting the accumulated delays in the architectural sciences. This is the thesis of the paper *COVID-19, design and social needs: an investigation of emerging issues* by Vito Getuli, Eleonora D'Ascenzi, and Saverio Mecca. Consequently, innovation must be based on a radically transdisciplinary approach between social, health and spatial sciences. A multidimensional analysis of texts in the scientific literature highlights central concepts and their relationships, showing the new centrality of socio-psychological and health issues for design at all scales.

In the essay *Towards a technical sentiment lexicon for the maintenance of human-centred buildings*, Marco D'Orazio and Gabriele Bernardini tell us about the paradigm shift affecting the human-building relationship, starting from the Cognitive Building concept nevertheless reworking it in light of Natural Language Processing (NLP) systems. The experimental case study proposes an innovative way of relating to the data produced *at capacity* by the pervasive digitization of buildings, particularly by Computerized Maintenance Management Systems. In the problematic Artificial Intelligence (AI) era, human behaviors return to the center through systems that model themselves in adaptive and interactive terms to produce *sensible* knowledge, programming and governance.

Natural Language Processing (NLP) is also the core topic of *Fostering the consensus: a BERT-based Multi-label Text Classifier to support agreement in public design call for tenders*, where Mirko Locatelli, Giulia Pattini, Laura Pellegrini, Silvia Meschini, and Daniele Accardo discuss the use of the method in the pre-design phase, which is at the moment an unexplored field of application, despite its wide use in the design and construction. The pre-design stage, heavily reliant on natural language, aims at connecting stakeholder needs and design proposals, opening the vision to co-design and community participation. The research presents a method to develop, assess, and evaluate an NLP tool, using the BERT language model, that translates quality needs and objectives into an assessment hierarchical grid.

A similar approach, based on a use case, is applied by Gianluca Maracchini and Elisa Di Giuseppe in the paper *Building energy consumption under occupants' behavior uncertainty in pre and post-renovation scenarios: a case study in Italy*. The authors center on a topic of pressing relevance: the gap between consumption predictions made in deterministic terms and behaviors that escape the model. Again, an experimental case study that, on the one hand, starts from real data to calibrate models and, on the other, develops new approaches to *governing uncertainty* from a sustainable transition perspective.

The importance of defined instruments and certified procedures for the green transition is relevant in the paper of Stefano Cascone, *Ecological transition for the built environment: natural insulating materials in green building rating systems*, where the author shows how the ecological materials for improving the thermal performance of the buildings and thus reducing their environmental impact are critical decision support issues. The document discusses and demonstrates how chemical products and traditional materials for refurbishment are not able to be included in the virtuous palette of sustainable interventions for the energy retrofit stressing how the NZEB approach (Nearly Zero Energy building) is going towards the evolutionary, the however not completely new, concept of LC-ZEB (Life Cycle Zero Energy building), including the embedded energy as a crucial energy amount to be reduced for the real inversion of the degradation of the global resource.

In the contribution *Testing and comparison of an active dry wall with PCM against a traditional dry wall in a relevant operational environment*, Marco Imperadori, Nicole Di Santo, Marco Cucuzza, Graziano Salvalai, Rossano Scoccia, and Andrea Vanossi analyze traditional wall (Dry Wall) and the false-wall with PCM (Active Dry Wall) to show the improvement on thermal performance of advanced insulation materials testing the solution in an experiment testbed. The case study and the monitoring of the thermal conditions of the envelope support the technological investment towards ZEB promoted by the national authorities and experimented by the test facilities of the polytechnic circuit. The energy and economic advantage is clearly demonstrated in winter, while future research on cooling needs and durability of the system could be beneficial to promote the diffusion of such advanced materials.

An innovative modelling approach that uses IFC (Internet Foundation Classes) not as commonly promoted as an information exchange format but as a data model, where standardized relations between building ontologies can be simulated, is proposed in the paper *Digitization of building systems using IFC to support performance analysis and code checking: standard limits and technological barriers. A case study on fire safety* where Carlo Zanchetta, Maria Grazia Donatiello, Alessia Gabbanoto, and Rossana Paparella aims at demonstrating how IFC ISO Standard can be used as a reliable data model to support Performance Analysis (PA) and code checking for construction disciplines using Fire Safety Engineering (FSE) as a challenging test field. The methodology consists of checking a digital approach to Performance Analysis based on information classes that can express users' requirements and performance specification of technical elements to develop computational code checking. This method is developed by creating virtual classes representing built systems and using relation classes and performance attributes to check if technical elements fulfil users' requirements.

A further innovative approach which is, in this case, focused on the evaluation of the compliance of school buildings with the measures to prevent and control the spread of Coronavirus, is presented by Carmine Cavalliere, Guido Raffaele Dell'Osso, Francesco Iannone, and Valentina Milizia in the contribution *Preventing COVID-19 spread in school buildings using Building Information Modelling: a case study*. The innovation relies on the methodology proposed to create a customizable and scalable rule-checking method for pandemics or other crises that invest in space management and users' safety. The methodology has been tested on school facilities as educational buildings are crucial in the continuity of the cultural progress of our communities, and societal protection can be supported by verification workflows based on digital technologies and Visual Programming Language (VPL).

To conclude, just as the Journal's call was being published, the two *topical* crises of the three years 2019-2022 (pandemic and climate change) were joined by a third: the eruption of armed conflict between major world powers, only seemingly confined to Ukraine, which radically alters the consolidation of a system-world (globalization). War and pandemics synergistically alter the process of global optimization of the economy and production, which had appeared unstoppable until the late twentieth century, downsizing the prospects of *inclusive prosperity* and replacing it with new resilient or *antifragile* approaches. The 11 contributions collected in this thematic issue are opening up the reflection on new visions that can be synthesized as follows in two main core topics:

- to restore the centrality of places and their specificities, meanwhile radically contradicting the postulate of hyper-specialization (and consequent productive de-localization). If the economy and its space are no longer guaranteed and secure on a planetary scale, local productions turn out to be preferable, both if referred to as strategic products or more trivial goods;
- to include an increasing factor of uncertainty and unpredictability in all planning and design processes. For example, the lean and material economy paradigms in structural calculations are revealed as factors of fragility.

THE ECOLOGICAL TRANSITION OF CITIES

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Federico M. Butera

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Abstract

The ecological transition of cities is crucial for the ecological transition of the entire world. This transition goes through the transformation of the current linear urban metabolism into a circular metabolism that mimics the functioning of ecosystems. A metabolism aiming to the minimisation of material inputs (products, water, food) in order to minimise both the withdrawal of resources from the environment and waste production. This goal can be achieved by adopting the principles of the circular economy, maximising the use of renewable sources and energy efficiency, and redesigning urban services, such as mobility and water-and-waste cycles.
In order to bring about this transformation, it is not enough to work on technologies and techniques because citizens' behaviour, lifestyles and cultural values are affected. Furthermore, treating the city as a living organism, i.e., as a complex system, requires an appropriate design and governance method underpinned by a systemic vision.

Keywords

Circular economy, Complex systems, Renewable energy, Planetary boundaries, Sustainable urban development.

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1. BACKGROUND

In 1950, only 30% of the world's population lived in cities, meaning by "city" an inhabited centre ranging from the biggest megacity to the smallest town. By 2020, the share of the urban population increased to 56.2%, and it is projected to reach 68.4% in 2050; in developed countries, people live already mostly in settlements (79.2%), while a lower share (51.6%) of developing countries inhabitants, including China, is urbanised [1].

Moreover, cities generate 85% of global GDP (Gross Domestic Product); they consume 75% of the natural resources entering the economic circuit, produce 50% of all waste, are responsible for 60-80% of greenhouse gas emissions (GHG) [2], consume 67% of all the food produced in the world [3], and it is estimated that by 2050 they will consume 80% [4]. Therefore, attention must be focused on cities because they catalyse most of the resources and economic activities and are the primary cause of environmental degradation. However, they are also innovation centres and can/should lead the way towards an environmentally and socially sustainable society.

Cities will grow mainly in developing countries, where they will require enormous amounts of resources for building up their infrastructures, from buildings to roads, and energy for their operation. At the same time, cities' growth will challenge the ecosystems, as urbanisation is also connected to the degradation and loss of forests, grassland, and marine areas (it is estimated that

90% of the wastewater in developing countries is discharged directly into waterbodies) [5].

2. CITIES' IMPACT ON GLOBAL ENVIRONMENT INTEGRITY

The current narrative on ecological transition is focused on the energy transition because of the more and more evident effects of climate change. This is a good starting point, but climate change is only one of the environmental problems we must solve, as shown in 2009 by a group of Earth system and environmental scientists [6]. They identified nine processes regulating the stability and resilience of the Earth system that we must keep under control and the nine limits that we must not transgress for maintaining planet Earth in the conditions that allowed the human civilisation and within which humanity can continue to develop and thrive for generations to come (Fig. 1). Crossing these boundaries increases the risk of generating large-scale abrupt, or irreversible environmental changes.

The nine planetary boundaries identified are:

1. Climate Change; caused mainly by the alteration of the CO_2 cycle through the increase in its concentration in the atmosphere. Other gases also contribute: methane, nitrogen oxides and fluorinated gases;
2. Chemical Pollution and the release of novel entities; namely radioactive compounds, heavy metals and a wide range of artificial chemical compounds and biological organisms;
3. Stratospheric Ozone Depletion; caused by human actions (emissions of CFCs, i.e., chlorofluorocarbons and nitrogen oxides);
4. Atmospheric Aerosol Loading; affecting the climate system and having adverse effects on health. It is mainly caused by burning fossil fuels and wildfires;
5. Ocean Acidification; caused mainly by the increase of CO_2 in the atmosphere dissolving in water;

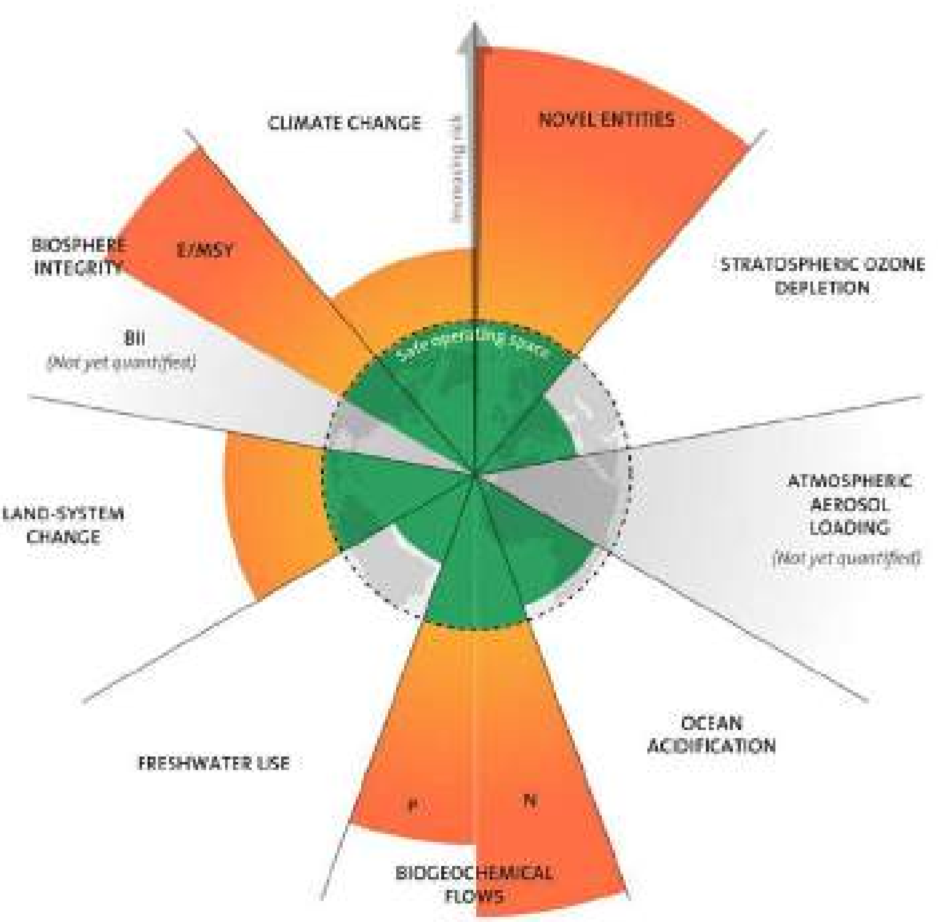

Fig. 1. *Planetary Boundaries [9].*

6. Nitrogen and Phosphorus Flows to land, water bodies and oceans; due mainly to the continuous input into the agricultural production system of large quantities of artificial nitrogen compounds and phosphates extracted from mines;
7. Freshwater Consumption; which has altered the Earth's hydrological cycle through the often senseless use of water resources in agriculture, above all, but also in industry and urban centres;
8. Land System Change; such as deforestation to create arable land, the transformation of wetlands into fish farms and grasslands into plantations, the expansion of cities, and the construction of transport infrastructure;
9. Loss of Biosphere Integrity; biodiversity loss and extinctions.

These nine processes are mutually interconnected and are all affected by urban resource consumption, which is also the main direct and indirect cause of some of their limits being exceeded.

The importance of the link between cities and the exceeding of planetary limits, i.e., between urban metabolism and the high risk of triggering catastrophic processes that will spare no one, is highlighted by the fact that limits have already been exceeded for the following five processes [7, 8]:

- climate change; cities contribute more than two-thirds of climate-changing gas emissions;
- modification of the biogeochemical cycle of nitrogen and phosphorus, primarily caused by food production, of which cities are the main consumers, and by not treated wastewater discharge;
- changes in land use, also mainly due to food production and by cities growth;
- novel entities, due to excess urban waste, food production and industrial chemicals pollution
- the loss of biosphere integrity, mainly caused by exceeding the four limits above and the pressure on the other four.

3. THE URBAN METABOLISM

«The notion of urban metabolism is loosely based on an analogy with the metabolism of organisms, although in other respects, parallels can also be made between cities and ecosystems. Cities are similar to organisms in that they consume resources from their surroundings and excrete wastes» [10].

The resources consumed are flows of materials, food, water and energy; once metabolised, these flows turn into waste, which is expelled in the form of greenhouse gases, wastewater, organic and inorganic solid waste, and low-temperature heat (Fig. 2).

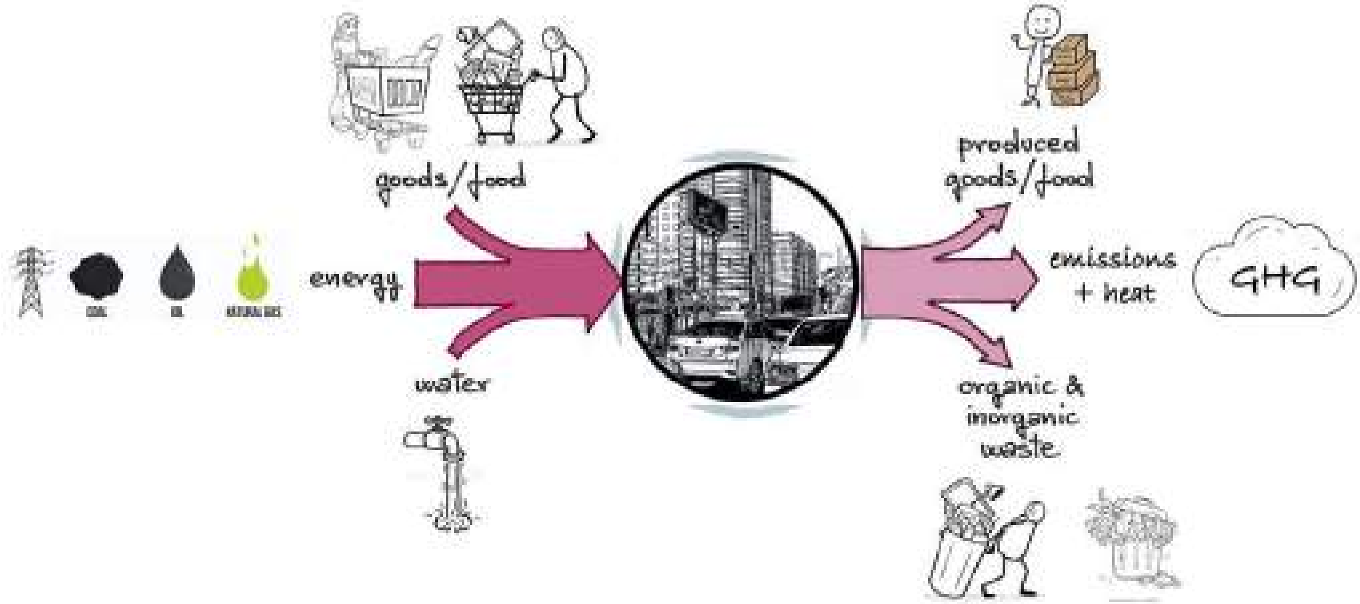

Fig. 2. *The urban metabolism.*

The metabolism of today's settlements is generally linear, i.e., the inputs crossing their borders are distributed inside the settlement and used to keep all the functions working; after their use, they are disposed of as waste outside the borders. In this model, the development and growth of the settlements are accompanied by a corresponding increase of inputs and, consequently, of waste, with increasing pressure on the environment's integrity. The linear "Take - Make - Dispose" lifestyle increasingly depletes finite natural reserves producing wastes in quantities that the environment is not capable of absorbing without damage.

3.1. ENERGY AND MATERIAL FLOW

People usually connect GHG emissions with energy consumption and are quite aware of the fact that heating and cooling buildings, lighting a room, heating water, driving a vehicle, etc., implies CO_2 emissions. For this reason, people – and policymakers – generally think that the problem of global warming can be solved simply by substituting the fossil fuel flow entering the city with a renewable energy flow.

Thus, the method used for the emissions inventory of a settlement is usually "production-based". This method captures GHG emissions associated with all significant urban activities within physical city boundaries, i.e., transport, buildings and industries, agriculture, forestry and other land uses (where applicable), as well as waste disposal and wastewater treatment. Emissions due to the production of the electricity consumed in the settlement are also accounted for, even if the production occurs in a power station outside the settlement's borders.

However, this accounting framework does not fully reflect the impact that cities have on global emissions, as it does not take into consideration the emissions associated with goods and services consumed in the city but produced elsewhere.

A consumption-based accounting framework should be used to include the climate impact of goods and services consumed in cities. This framework allocates all GHG emissions associated with the production and distribution of goods and services to the final consumer, allowing for the total GHG emissions associated with city residents and, by association, the businesses and institutional activities serving them.

The consumption-based approach captures both direct and lifecycle GHG emissions of goods and services (including those from raw materials, manufacture, distribution, retail and disposal), and allocates GHG emissions to the final consumers of those goods and services rather than to the original producers of those GHG emissions. GHG emissions from visitor activities and the production of goods and services within the city boundary that are exported for consumption outside the city boundary are excluded.

In simple terms, a consumption-based GHG inventory can be defined as the emissions arising within a city's boundaries (production-based emissions) minus those emissions associated with the production of goods and services exported to meet demand outside the city, plus emissions arising in supply chains for goods and services produced outside the city but imported for consumption by its residents, the so-called embodied emissions.

To give an idea of the gap between the two accounting frameworks, an evaluation [11] carried out for the C40 cities (a network of the world's megacities committed to addressing climate change) shows that 85% of emissions associated with goods and services consumed in C40 cities are imported from elsewhere (including electricity) and only 15% produced within their borders.

From the consumption-based approach, the set of actions to implement for minimising or zeroing the settlements' GHG emissions can be derived, starting from the evidence that there are two emission sources to consider, the produced ones and those embodied in the goods, services and food imported.

On the other hand, any product is not only the cause of greenhouse gas emissions, i.e., it has a carbon footprint, but it also has a water footprint (the water used for its production). Any product is also the cause of aerosol emissions (which affect the global climate, as well as being harmful to health), and, in many cases, it is the cause of the release of novel entities into the environment (the chemicals used in the production process, plastics, etc.); it is also indirectly the cause of ocean acidification and, through the extraction of raw materials and the cities growth, is a cause of land use change. Suppose we focus on agricultural products, which are a non-negligible part of the flow of matter feeding the urban metabolism. In that case, we see that they have a tremendous impact on the planetary boundaries' transgression. This is because food production, in addition to contributing 24% to global greenhouse gas emissions and being the leading cause of the overshooting of three planetary limits (biogeochemical flows, land use change and biodiversity loss), also has a heavy impact on the global use of water and is a significant cause of the introduction of new entities (herbicides, insecticides, fungicides, antibiotics, hormones, etc.).

We may conclude that the flow of goods entering the cities is the main cause of their impact on planetary boundaries and, given their weight on global environmental degradation, this flow is the first responsible for the present planet's sickness.

4. REDESIGNING THE URBAN METABOLISM

To reduce the cities' impact on the environment, a new metabolism model is needed to simultaneously lower resource consumption, i.e., material input, and waste production. A metabolism which tries to mimic the way ecosystems work, where it is always the same amount of matter circulating, used and reused an infinite number of times, the cycle being powered by solar energy, and where the concept of waste does not exist. Key issues to be addressed in a different way are: consumed emissions, goods, water and nutrient flows.

4.1. MINIMISE CONSUMED EMISSIONS

The large majority of buildings nowadays use power for lighting, electric appliances and all the electronic devices our houses are full of. The power demand of buildings has been growing in the last few years, especially for the growing number of electric and electronic equipment. Despite this growth, however, in temperate climates buildings, the largest share of energy consumption has been due to fossil fuel combustion to provide space heating and hot water. In order to achieve the net zero emissions goal, there is broad consensus on the need for also electrifying space heating and hot water production by means of heat pumps instead of gas or oil boilers. This choice is obliged, as zero-emissions electricity can be produced using PV panels and wind turbines, and heat pumps are the most efficient technology for providing the services requested.

Buildings' roofs can host PV panels, transforming households from power consumers into power prosumers, as they also produce electricity. Moreover, buildings host, more and more frequently, electricity storage systems, i.e., batteries, that can be shared among a few prosumers mutually interconnected to build up an energy community. A sustainable city is made of renewable energy communities.

Then, there is the issue of building materials' embodied emissions. An issue that will be more and more important as the energy needed by buildings operation will be renewable. In the very end, if renewables fully provide the building's operation energy, the only emissions are the embedded ones, and materials like cement and steel, which have very high embodied emissions, must be used carefully.

The global environmental impact of the materials' use in buildings is very high: it is estimated that 46% of the world building stock in 2050 will have been built between 2015, i.e., the world building stock in 2050 will have almost doubled [12].

Thus, the main issue for architects designing present and future buildings is the choice of materials, looking for the least impactful. This objective requires the development of new materials and the wise use of existing, low-emission materials. New building regulations will be necessary to make the use of low-emission materials mandatory. There is already a growing variety of low-emission and low-environmental impact new materials and components, but the problem is to have their environmental performances certified. At the same time, learning to reuse the building material resulting from excavation and demolition is essential instead of sending it to a landfill.

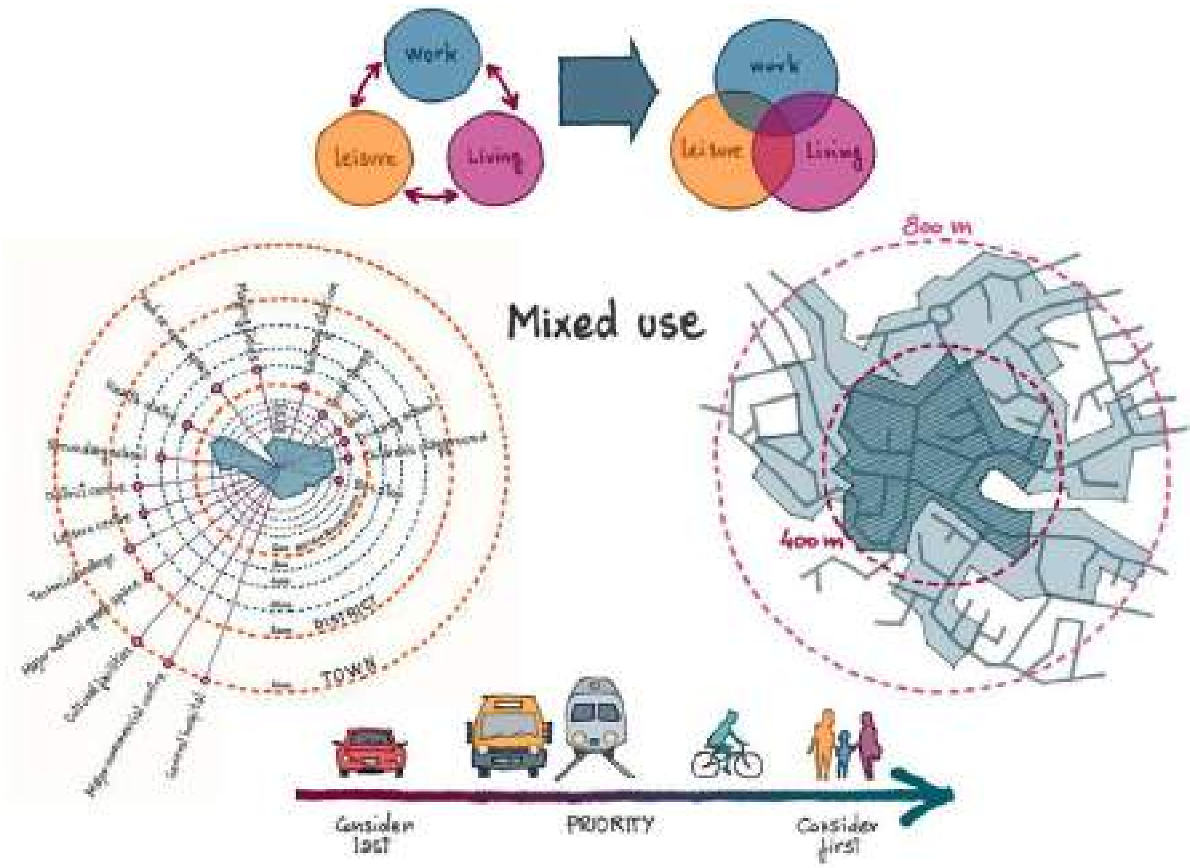

Fig. 3. *Five minutes' walk strategy.*

The way a neighbourhood is conceived has a substantial indirect impact on GHG emissions due to motorised transport. In fact, building and neighbourhood design is also connected with mobility in many ways. The main connection is related to the 5 minutes' walk strategy (Fig. 3), which is based on the idea that all the places a citizen needs to reach with high frequency are within a maximum 5-10 minutes walk from home (the best is 5 minutes, according to sustainable urban planning literature; Paris, instead, is implementing the 15 minutes city approach). These places are those related to education, work, knowledge exchange, shopping, recreation, community engagement, health, public transport, exercise, and nutrition. This approach is the so-called mixed land use, opposite to the one based on the spatial separation of main urban functions (work, living, leisure) that has been driving 20th-century urban development.

The implementation of such a strategy reduces so much the need for a car that most citizens will give up theirs and will move to walk or ride a bicycle – and use car-sharing services when occasionally the car is unavoidable. In this vision, vehicles are electric and powered by renewable energy.

The connection between neighbourhoods' design and GHG emissions is further reinforced by the fact that by making car ownership useless in most cases, the number of cars would significantly be reduced, accordingly reducing the amount of embodied emissions, as new vehicles would not be built.

Buildings and mobility will be more intertwined with the growth of electric cars, as their battery can be used as electricity storage for a single building or as distributed storage for the grid.

4.2. THE CIRCULAR ECONOMY MODEL

The adoption of the concept of circular economy is crucial. The transition to a circular economy, where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised, should be the driving principle in the design of a city in order to be sustainable (Fig. 4).

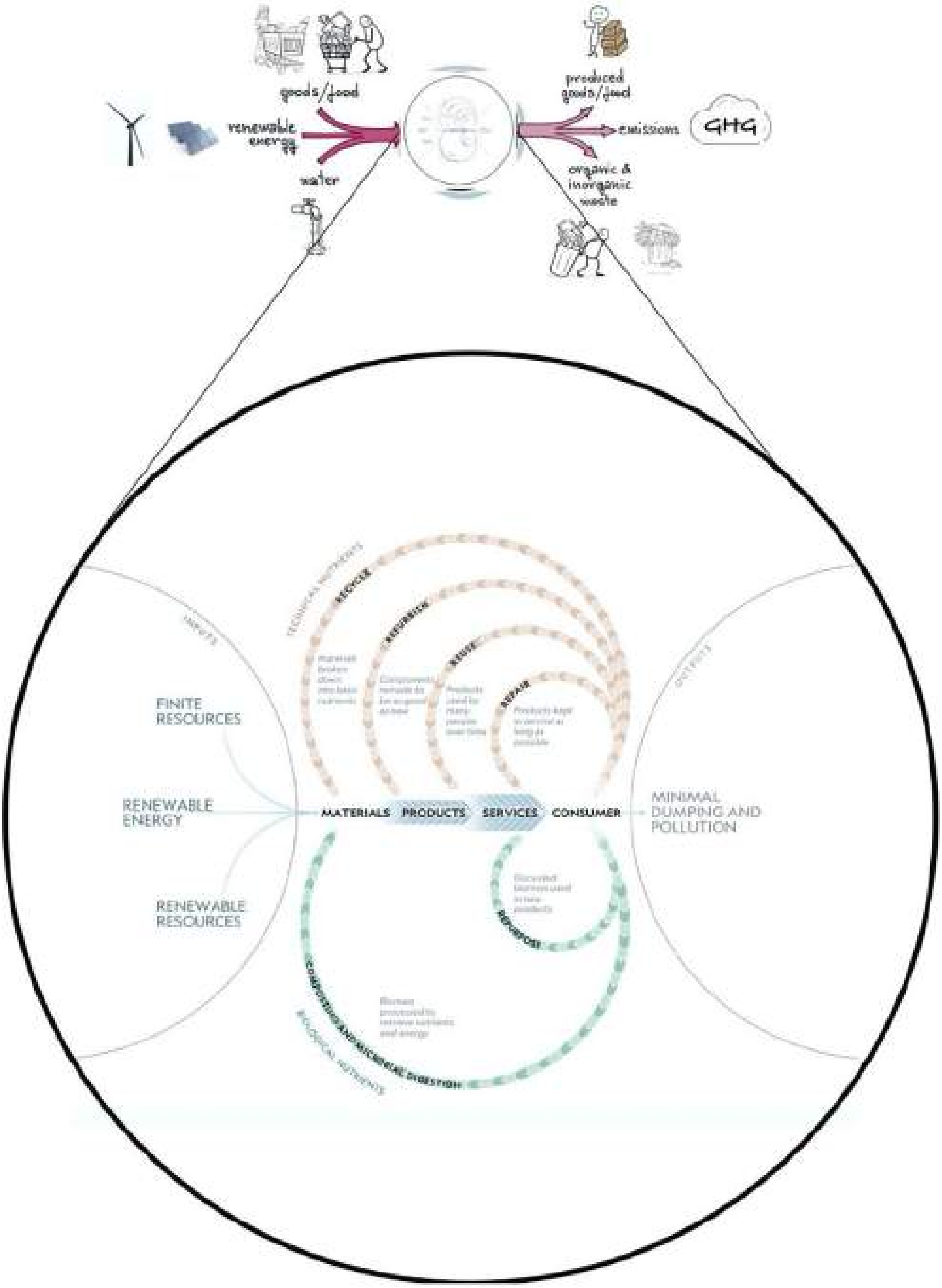

Fig. 4. *Circular metabolism (adapted from National Geographic, https://www.nationalgeographic.com/magazine/article/how-a-circular-economy-could-save-the-world-feature).*

Circular economy pillars are, among others [13]:

- improving product durability, reusability, upgradability and reparability... and increasing their energy and resource efficiency;
- increasing recycled content in products while ensuring their performance and safety;
- enabling remanufacturing and high-quality recycling;
- reducing carbon and environmental footprints;
- restricting single-use and countering premature obsolescence;
- introducing a ban on the destruction of unsold durable goods;
- incentivising product-as-a-service or other models where producers keep the ownership of the product or the responsibility for its performance throughout its lifecycle.

It is a sort of revolution. It involves a shift from a production-based economy to a mixed economy, in which production is strongly reduced, and maintenance is increased. It also changes the labour market, offering great potential for new activities and jobs.

The effects of circular economy adoption are multiple. One is the reduction of the consumed emissions, as the amount of goods entering the city is strongly reduced, along with the flow of embodied emissions. Another effect is reducing the amount of material extracted from the environment, with consequent lesser impact on ecosystems, water and land use, and novel entities pollution. But the most revolutionary effect is on our economic system. Indeed the basis on which it is presently built, consumerism and the unlimited growth of the production of goods and services, is seriously challenged, as well as the unlimited growth of GDP.

Our addiction to the current lifestyle is seriously challenged, based on a compulsive need to consume, induced by a prevailing culture in which the more you have, the better you are. Circular economy adoption implies restoring an old and forgotten value: sobriety.

4.2.1. CIRCULAR ECONOMY APPLIED TO WATER

We must view water as part of a circular economy, in which it retains full value after each use and eventually returns to the system: a system in which water circulates in closed loops, allowing repeated use. Sustainable water management embraces the following:

- conservation of water sources;
- use of multiple water sources, including rainwater harvesting, stormwater management and wastewater reuse;
- treatment of water to the extent it is needed, exploiting the energy that wastewater can produce for the benefit of the settlement and the nutrient potential of wastewater for the benefit of urban and peri-urban agriculture.

Water, in cities, is not only a crucial issue in terms of environmental impact but is also crucial as a cause of damage to cities' activities and infrastructures because of the more and more frequent excessive precipitation and consequent flooding.

Thus, water is a critical issue also in terms of adaptation to the effects of climate change.

4.2.1.1. Rainwater harvesting

Rainwater harvesting can reduce pressures on rivers, lakes, and other water sources and help prevent urban flooding by reducing storm flows. It should be considered for non-potable uses.

In the new perspective of ecological transition and of many decades of altered climate, rainwater must be considered in designing new urban developments.

4.2.1.2. Decentralised wastewater management

Wastewater produced by households is usually subdivided into black water, grey water and stormwater. Black water is the wastewater from the toilet and kitchen sink; grey water consists of the wastewater from washing/bathing and washing clothes.

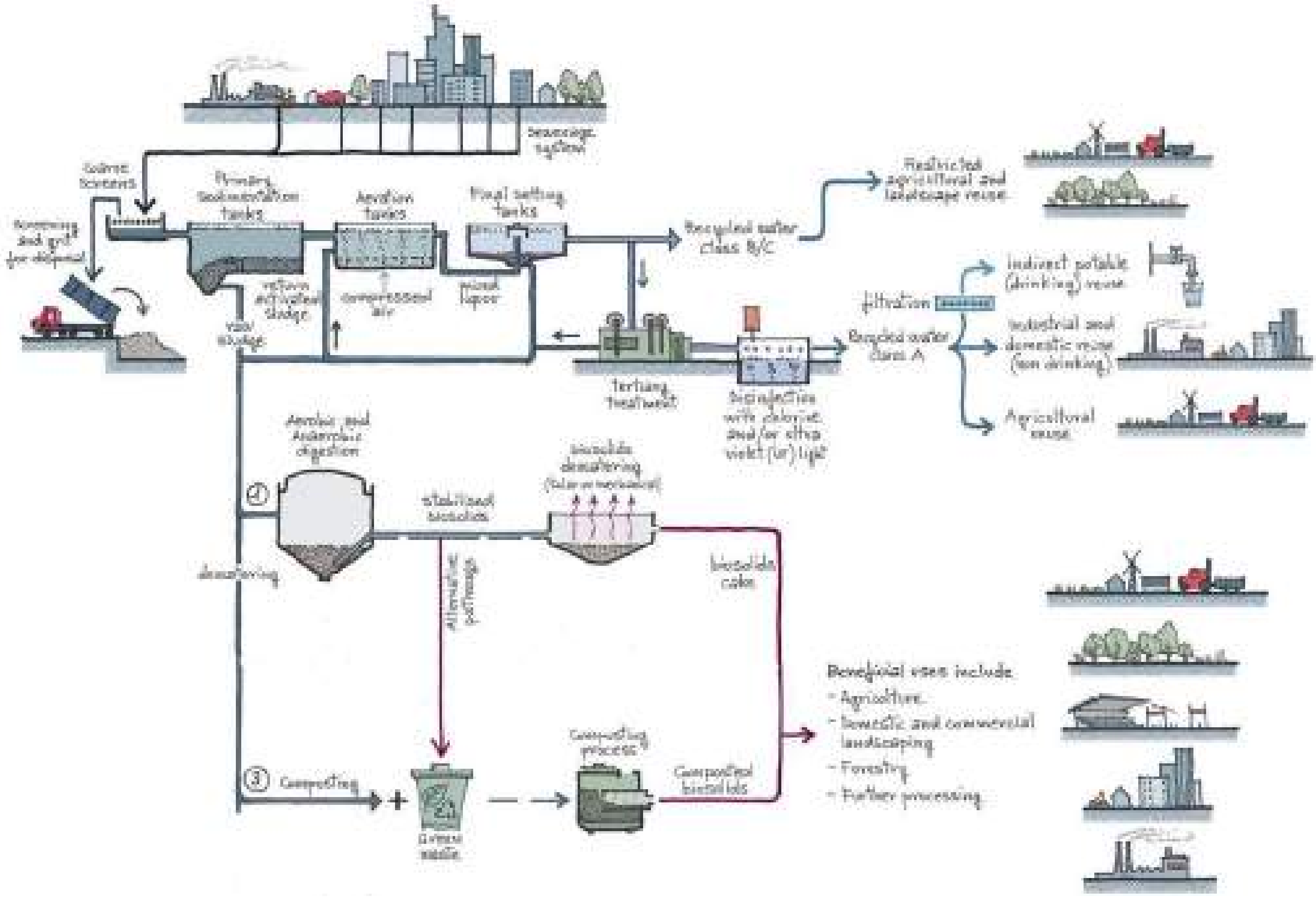

Fig. 5. *Wastewater treatment.*

What usually happens is that the three water sources are all conveyed to the sewage, mixed, and then sent to the centralised wastewater plant. It would be far better to collect rainwater separately and treat grey water locally, as it requires a simple process because of its low level of contamination, reusing it locally for non-potable uses such as toilet flushing, laundry washing, plant watering, etc. The reuse of rain and grey water can potentially reduce the demand for water supply from outside, more or less faraway sources, and reduce both the carbon and the water footprint of water services.

On the other hand, reusing grey water and/or the direct use of rainwater requires dedicated piping other than the usual one for potable water.

The treatment of black water, mixed or not with grey water, is a more complex issue because of health hazard implications. The current trend is to centralise the treatment system.

Wastewater treatment plants are based on biological processes. The treatment can be carried out either in the presence of oxygen (aerobic system) or in its absence (anaerobic system). At the end of the process, we have a flow of clean water that can be used for irrigation, a flow of sludge that can be used as fertiliser, plus, in the case of the anaerobic system, a flow of biogas (Fig. 5).

Unfortunately, both treated water and sludge are very often not reused, but wasted by, respectively, pouring it into water bodies and sending the dried sludge to the landfill or incineration.

Biogas production is rare in cities' treatment plants, even if the benefits of anaerobic digestion of sewage sludge are widely recognised, and the technology is well established.

4.2.2. CIRCULAR ECONOMY APPLIED TO SOLID WASTE

According to the principles of the circular economy, the first action in solid waste management should be a reduction in the inflow of goods, which is the primary cause of the waste flow.

For example, packaging can be reduced by encouraging the sale of unpackaged products; reuse can be facilitated by implementing a deposit return scheme for bottles and cans; the repair of appliances and clothing can be encouraged in several ways; single-use goods can be banned or discouraged; and so on.

In such a city, the amount of inorganic solid waste would be significantly reduced. It would be separated at origin (i.e. by citizens before their collection) into the main types, such as glass, metals, paper, and others, and then sent for recycling.

The first priority in reducing organic waste is reducing food waste. This action requires two combined efforts:

- reduction of the excess food purchased, which implies behavioural change;
- increase the number of proximity shops where food can be bought every day, instead of driving to a supermarket every week, which implies using the car and often purchasing more food than needed.

After measures have been taken to reduce organic waste, this should be introduced into the nutrient cycle and exploited for its energy potential.

The best is to use food waste to feed an anaerobic digester, thus producing biogas and a slurry that can be used as fertiliser directly or after appropriate processing.

To complete the closure of the city's organic waste cycle, branches from tree pruning could feed a gasifier, also producing biochar which can be used as a soil improver.

4.2.3. CIRCULAR ECONOMY AND REGENERATIVE AGRICULTURE

Circular economy adoption implies restoring the nutrients cycle, the cycle of all those substances contained in the food we eat that are essential to our physical well-being and health. At the world scale, only a tiny fraction (2%) [3] of nutrients in the food, which are then contained in our excreta, return to the soil from which they came. These nutrients are lost and replaced with artificial fertilisers. Hence the need not only for a different treatment process of black water and food waste but also for a new close input-output interaction between settlements and the surrounding rural areas. But this is not enough, as the way food is produced must also be changed.

Cities can significantly influence the way food is grown, particularly by interacting with producers in their peri-urban and rural surroundings. Regenerative approaches to food production will ensure the food entering cities is cultivated in a way that enhances rather than degrades the environment and creates many other systemic benefits, such as protecting our health.

Examples of regenerative practices include shifting from synthetic to organic fertilisers, employing crop rotation, and using greater crop variation to promote biodiversity.

Regenerative practices support the development of healthy soils, which can result in foods with improved taste and micronutrient content. Cites cannot, of course, implement these techniques alone. Collaborating with farmers, and rewarding them for adopting these beneficial approaches, will be essential.

Cities can source a large share of food from their surrounding areas: 40% of the world's cropland is located within a 20 km radius around urban boundaries [3]. Cities can use their demand power to influence peri-urban farmers to adopt more regenerative practices and, at the same time, return nutrients to peri-urban farms in the form of organic fertilisers derived from urban food waste and wastewater.

While local sourcing is not a silver bullet, reconnecting cities with their local food production supports the development of a distributed and regenerative agricultural system. It allows cities to increase the resilience of their food supply by relying on a more diverse range of suppliers (local and global) and supporting native crop varieties. It allows city dwellers to strengthen their connection with food and the farmers who grow it, often increasing the likelihood that people will demand food grown using regenerative practices that benefit the local environment and their health. Local sourcing can also reduce the need for excess packaging and shorten distribution supply chains.

5. GOVERNANCE OF THE URBAN TRANSITION TO SUSTAINABILITY

It has been shown that the most effective approach for driving a settlement along the sustainability path involves several actions covering a large spectrum of issues, ranging from energy production to flood prevention, from mobility to waste management. Not only are technological changes needed, but also the way city life is organised must change, as the circular economy requires. Citizens' lifestyles must change, changing the values that move their actions, cultural values that are intangible but crucial factors in the difficult path to sustainability: no more consumerism, but sobriety, reflecting the principle of sufficiency. Less competition and more cooperation. Solidarity and, precondition of the ecological transition, less inequality.

All these items, and the technical/technological ones, are tightly interconnected: we must be aware that the city is a complex system. This knowledge implies a methodological change in the planning approach.

The usual approach has been the one developed within a reductionistic view of reality: there is a problem, let's split it into parts, analyse each piece and try to optimise it, with the belief that if each part is working properly, also the entire system will perform at best. This approach is intrinsically wrong because in a complex system, as a settlement is, problems must be faced with a system approach, highlighting the crucial role of the interconnections between the subsystems. Interconnections that are not always explicit at a first analysis may become evident as a consequence of new actions that alter the previous status of the system. With the ecological transition, something new has to be faced: the city we want to realise is profoundly different from the present one, and we do not have examples to refer to. This evidence, coupled with the need for a system approach, requires the adoption of a planning methodology different from the usual one, such as backcasting.

Backcasting is a planning method that starts with defining a desirable future and then works backwards to identify policies and programs that will connect that specified future to the present.

While forecasting involves predicting the future based on current trend analysis, backcasting approaches the challenge of discussing the future from the opposite direction. It is a method in which the desired future conditions are envisioned, and steps are then defined to attain those conditions rather than taking actions that are merely a continuation of present methods extrapolated into the future. Thus, once the long-term vision is agreed upon among all the stakeholders (citizens, institutions, entrepreneurs, etc.), each action implies checking both the feasibility in the present and the compatibility with the vision of the future. This process will not be linear or straightforward, being the city a complex system, but will follow an adaptive path, similar to steering a sailing boat: you start from a port and want to reach another port, but you cannot go there straight, because your route depends on wind, currents, waves, the type of boat and the skill of the skipper. Sometimes you may have to go very far from the target port or even go backwards or stop temporarily in another harbour. When you sail towards the selected port, it is also possible that something has changed inside the boat o in the originally desired port, and a new port is chosen. And each change of direction along the journey has to be agreed upon among crew and passengers.

Not an easy task, indeed. But a challenge we have necessarily to face.

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ENVIRONMENTAL ETHICS AND SUSTAINABILITY OF TECHNIQUES. FROM HYPER-SPECIALISATION TO MULTIFUNCTIONALITY FOR A RESILIENT INHABITABLE SPACE

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Abstract

Crises represent crucial global dynamics events, which were predictable and have been with us for some time. In the new context caused by epidemic and pathogenic conditions, not only must it be reaffirmed that planetary society is an integral part of nature, but that the production processes of anthropogenic metabolism are part of the more general metabolism of nature. Climate change, a significant element of the contemporary environmental crisis, will orient living conditions within the global ecological crisis in a different way.

The concept of habitable space, which is, above all, a space of correlation between society and the environment, considers technology as a factor in the reconstitution of a process that is symbiotic and no longer of exploitation of environmental resources. Recently, there has been a renewed awareness of place consciousness and of inhabitants/producers who, through a co-evolutionary principle, are called upon to develop "neo-ecosystems" according to a territorial identity principle.

Rather than representing levels of identity that nevertheless express borders, the "local" category constitutes what is discussed and argued in common through a measure of involvement and intensity. So, the relationship between transition cities and urban resilience is part of the governance of the new phenomena of non-linearity. In metropolitan areas, the spread of new urban polarities evolves the concept of resilience towards a multi-scalar and multi-sectoral condition of adaptation and mitigation of anthropogenic and environmental risks.

Inside this scenario, hyper-specialisation still represents the tendency of a technical character that induces the development of deep competencies but loses the critical sense of technique in its ethical and socio-economic interactions. Inhabiting and building evolved scenarios of society need a multifunctional thought that can develop and critically manage the choices and uses of technology in a design scenario capable of coherently integrating its contributions.

Keywords

Climate adaptive design, Risk management, Urban ecodistric, Resilient habitat, Environmental design.

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1. ECOLOGICAL LIMITS AND ENVIRONMENTAL ETHICS. FROM RELATIONSHIP TO THE INTERACTION BETWEEN MAN AND ENVIRONMENT

The roots of the multiple crises that are straining the planet – climate, energy, pathogenic crises, etc. – are mainly found in an economy that does not respect ethical limits and is based on the inexhaustibility of resources, causing inequalities and clashing with the ecological limits of the planet [1]. Thus, ecological crises cannot be separated from the economic and social systems that support them [2], as the interference of human actions with natural phenomena has reached thresholds of no return, with heavy social and economic as well as environmental and ecosystem impacts. On the other hand, the significant problems of our time cannot be understood in isolation because they are systemic, interrelated, and interdependent problems, non-linear in nature, as they are representative of the connotative aspect of networked patterns of living systems [3].

During the recent pandemic, environmental concerns have long been overshadowed by events at the UN-sponsored Conferences of the Parties (COP). COP 27 in Sharm el Sheikh in November 2022 highlighted the need for compensation of poor countries that have suffered loss and damage from anthropogenic climate change, while at COP 26 in Glasgow in November 2021 – within a more robust integration between adaptation and mitigation goals – the link between environmental crises and ecosystem balance was pointed out. As Slavoj Žižek points out, it is necessary to reaffirm the substantial unity of the two spheres, as the epidemic has exploded due to the unbalanced relationship between the economy, society, and the environment [4].

The crises represent crucial moments in the dynamics of global capitalism, which were not only predictable but have been with us for some time. In the new context brought about by epidemic and pathogenic conditions, it must be reaffirmed that planetary society is an integral part of nature. Moreover, the realisation of production processes that represent anthropogenic metabolism is part of the more general metabolism of nature. Climate change, a major part of the contemporary environmental crisis, will have to orient living conditions within the global ecological crisis differently.

It will be necessary to recognise the human-environment correlation within broader connections between the living and physical worlds. If, in pathogenic conditions, humankind struggles against external agents, ecological mutation gives rise to a tragically reversed situation in that the agent that has altered the living conditions of all the planet's inhabitants is not a virus at all but human society [5]. Suppose the ecological footprint has exceeded the planet's capacity to withstand the production and consumption processes of the entire Anthropocene society. In that case, the emission of climate-altering agents can be controlled by combining the efficient use of energy with the reduction of the production volume of materials and their flows within the entire environmental system [6].

Based on the new conceptions of nature and humans, in the reciprocal dependencies between agents, knowledge and actors, environmental ethics simply relocates man and his activities within nature, allowing people to look at the world feeling part of it and abandoning anthropocentrism that has lost its legitimacy. Environmental ethics is based on the idea of the ecosystem, in which all living beings are part of complex and mutually interacting life forms in both the biotic and abiotic environment. In contemporary times, the focus on living beings as organisms to be safeguarded is shifting to preserving the entire earth system, understood in its overall physical components and habitats that are home to living species.

The underlying theme of an evolved perspective for environmental ethics is no longer to transform the environment in a compatible manner or to preserve it but to understand what point of view to adopt and what actions to ensure the continuous interaction between human activities and the environment without compromising the ecosystem balance.

2. IN THE AGE OF TECHNIQUE: PROMOTING REGENERATIVE PROCESSES FOR HABITABLE SPACE

Bruno Munari relates the meaning of inhabitable space to research carried out in the period of outstanding youth cultural ferment around 1968 and oriented towards the future by proposing a lifestyle that would make the economy of space and resources its strong point for greater flexibility in housing. B. Munari, L. Forges Davanzati and P. Ranzani presented the *Spazio Abitabile* project at the 14th Triennale in Milan in 1968, looking at the young people who would inhabit the future with a view to enabling them to obtain a comfortable home without high costs. Within the problems of number and quality, the reference to "modulated blocks" would have made it possible to integrate the indispensable furnishings, leaving the inhabitants free to intervene with their personal choices [7].

The notion of habitable space was thus born on the basis of a forward-looking perspective. While Munari placed the concept in the indoor space, a few years later – in 1973 – Eduardo Vittoria implemented an extension to the entire "empty space of the habitat", extending the concept to the space of human interactions with the surrounding environment. Research on habitable space represents the outcome of several technological possibilities capable of conceiving and modelling artefacts in an innovative manner, establishing a bi-univocal relationship between people and the environment considered in its various physical, biological and cultural components [8].

While being closely interconnected components, it was not possible to enucleate artefacts from the environment itself, conceived as an integrated system between the natural and the built environment. This concept of habitable space, which is, above all, a space of correlation between society and the environment, considers technology as a factor in the reconstitution of a process that is symbiotic and no longer of exploitation of environmental resources. It should be recalled that in those years, Tomás Maldonado emphasised overcoming the legacy of idealism. He suggested considering the value of the city as an existential operating territory, in which the inhabitants were actors that operate and live in the city and not spectators of an aesthetic landscape. According to this consideration, a scientific approach to the order/disorder dichotomy was advocated, whose polarisation was inseparable from the simplicity/complication pair [9].

Recently, there has been a renewed awareness of place consciousness and of inhabitants/producers who, through a co-evolutionary principle, are called upon to develop "neo-ecosystems" according to a territorial identity principle. The place is not understood according to a relational meaning but as an identity factor capable of generating innovative communities, behaviours, cultures and ecological techniques of living and producing [10]. By grouping, human express a capacity to situate themselves and be localised by making an evolved sense of the conception of the "local". Rather than representing levels of identity that nevertheless express borders, the category of "local" constitutes what is discussed and argued in common through a measure of involvement and intensity, according to a controlled logic of reduction of the relationship between "small" and "large" [11].

In the ecological crisis, we are aware of the ever-increasing contribution of technology and its risks, as economic and productive forces and great socio-technical development require a constant reorganisation of production processes and urban systems. Directing technology towards levels that are functional to sustainable development and capable of interacting with environmental ethics today represents the relevant challenge to be implemented through a fair and sustainable development model, capable of guaranteeing the survival of ecosystems and the environment in all its complexity.

The outcomes of transformation processes and all the products of anthropisation are placed within the horizon of technology, in which every project is part of the production. «With metaphysics, nature has been measured by human design»: thanks to science and technique, man has no longer considered nature as his home but as raw material for his production and consumption [12]. Bruno Latour points out how habitat and inhabitants represent a continuum since defining one is equivalent to specifying the others. Consequently, the city is nothing more than the exoskeleton of its inhabitants since nothing on Earth is entirely natural since everything is the effect of the actions performed by living organisms [11]. In this way, we can understand how today, the crucial condition is represented by overcoming the short circuit according to which «it is no longer ethics that chooses the aims and entrusts technique with finding the means, but it is a technique that, taking the results of its procedures as aims, conditions ethics, forcing it to take a position on a reality that is no longer natural but artificial» [12].

A line of action for the future is oriented towards the transition of "regenerative" cities, capable of implementing the development of circular metabolisms and processes that progressively replace conventional and essentially linear processes to support efficient and low-waste projects and processes. Every action of urban and environmental conservation or transformation requires to be seen as a process of ecosystem reactivation through the use of appropriate strategies and technical and design solutions of rebalancing. These should be directed at bridging gaps in biodiversity mixite, efficiency and effectiveness of processes and life cycles, favouring approaches for a new ecology of the artificial and natural environment [13].

Within this reactivation pathway and alongside the sustainable use of resources, managing processes and projects should ensure that simultaneous environmental regeneration creates conditions favourable to life for all biotic and abiotic components. A regenerative approach provides the proper interactions between the anthropised environment and the natural environment, guaranteeing well-being and minimising the use of energy and matter in all phases of production and consumption cycles, with reuse, repair, restoration and recycling. Regenerative factors help to maintain a balance through the resilience of contexts that can counter and react to the impacts of environmental, natural and anthropogenic hazards.

Regenerative logic for urban contexts can become the basic code for innovative actions that modify the metabolism of cities in which resources are introduced into the urban system by separating inputs from outputs without considering the origin of the former nor the destination of waste at the end of transformation processes. Instead, by pursuing process efficiency, the reduction of resource consumption or the use of renewable resources, the circular process model emphasises how much one must act in the direction of keeping products, components and materials as long as possible at the highest level of performance. This fact orients industrial production for the built environment towards durability, simple replacement and long life of products within the environmental system.

In interventions at different scales and in the architectural field, technological solutions are required to support new organisations of urban districts and buildings to progressively reduce the impact due to technological cycles that are incompatible with natural cycles. The logic of buildings that are not very durable and require progressive and substantial maintenance will have to give way to building concepts that, by design and construction prerogatives, can minimise maintenance in favour of affordability and durability.

The role of transition from urban districts to eco-districts becomes central in transforming the living space of entire urban areas and buildings in which every activity aims to regenerate the natural capital according to harmonised times and modalities. A regenerative city is not only a green city that interacts with nature but is, above all, an example of the reconversion of urban activities according to a strong interaction between technology and the environment, between urban systems and the ecosystems in which they are embedded.

3. INTERACTIONS BETWEEN TECHNOLOGY AND ENVIRONMENTAL ETHICS: MULTIFUNCTIONALITY VS HYPER-SPECIALISATION IN THE PERSPECTIVE OF THE RESILIENCE OF HABITABLE SPACE

In its general meaning, the concept of resilience represents the capacity of a system to regenerate and reorganise itself after adverse events, proportional to the amount of disruption the system can absorb as well as its ability to self-organise, learn and adapt [14]. In resilient terms, architecture relates to forecasting and prevention strategies, adaptation to impacts, reduction of vulnerabilities and programming of measures for risk mitigation. The resilience of territories, cities and buildings, therefore, represents the new challenge in today's "risk society", in which it is necessary to combine design and innovation with reference to conservative, adaptive, reactive and regenerative capacities aimed at reducing vulnerabilities and minimising the impacts resulting from extreme and unforeseen events.

The topic of resilience concerning natural and anthropogenic hazards is connected to functional-spatial and environmental conditions, processual and governance aspects, and technical-constructive ones, which require the implementation of forecasting and prevention strategies [15]. The relationship between transition cities and urban resilience is part of the governance of the new phenomena of non-linearity. In metropolitan areas, the spread of new urban polarities evolves the concept of resilience towards a multi-scalar and multi-sectoral condition of adaptation and mitigation of anthropogenic and environmental risks. Finally, the hazard-specific and site-specific situation of resilience is addressed by identifying and constructing integrated scenarios for its measurability and for developing projects, products and processes aimed at reducing both resource requirements and environmental impacts [15].

A resilient system is a system based on an adaptive cycle that has several characterising phases: the first of rapid growth, the second of conservation, and the third of release in which resources are dispersed following an unforeseen impact, while the fourth phase constitutes the moment of reorganisation in which the cycle restarts [16]. Dynamism and diversification are characteristics of resilience, which is based on feedback processes of dynamic reorganisation. Figuratively speaking, resilient systems are diversified at the margins but exhibit simple and effective behaviour at the central “core”, ruling out the possibility of one part’s vulnerable conditions cascading to others. Resilient systems’ regenerative and reorganising capacity manifests itself by operating under variable conditions, reacting flexibly from a predefined state to one that arises unexpectedly.

This characteristic allows a complex system to adapt to new operating conditions and improve its adaptive capacity by maintaining, integrating or replacing some of its own functionalities to preserve an operational life aimed at the system’s purpose.

Moving away from the hyper-specialisation inherent in modernisation and relying on a transition that sees the ethical values of the environment and ecology at its centre also becomes a motif of cultural transition. A new ontological definition of the technique and design of habitable space drives its multifunctionality and the multiculturalism that should underpin it. The values expressed by collateral qualities such as flexibility, horizontal integration, circularity and resilience find a foothold in complex thinking, in which the awareness of uncertainty is combined with risk awareness and the application of a prudential principle [17].

It is necessary to realign the project for the built environment to the new perspectives of inhabiting. Edgar Morin recalls how there is always an ecology of action in which every decision, other than being a promise of a result, is also a bet on the effectiveness of the expected result: overcoming abstract logic and the idea of dogmatic reason, there is a continuous need for complex rationality that copes with contradictions and uncertainty without repressing them [17]. The heuristic process of the architectural design, which must be able to take into account unforeseen variables to unfold its path of research, also includes conditions of doubt and uncertainty, fits into this direction.

An interpretation of the change of scenario in the transition from classically understood modernity to the new complexities of the contemporary world must be set out by considering the relationship between space and socio-economic conditions. This consideration highlights the overcoming of modernist ideology and the production/consumption cycle closely linked to spatialisation or functional specialisation, the rational centralisation or decentralisation of functions, the spatial division of labour and the homogenisation of productive activities through spatial segmentation [18]. In the field of architectural design, these data find, for example, clear evidence in neighbourhoods with functional specialisations (residence, directionality, commerce, services and equipment) or industrialised building production in closed cycles, where linear and mechanistic processes are prevalent.

The evolution and transformation of contemporary scenarios respond to a unified spatiality through mixite and aggregation of fragmentations for the constitution of new identities, developing according to the new values and conceptions of spatial integration, diversification and flexibility of urban space as well as the multiple finalisations of spatial proximity [18].

The radical break with the mechanistic, unifying, hyper-specialised and hyper-functionalist horizon of modernisation is implemented through progressive departures from Fordism as ideology. The new scenarios are outlined by flexible accumulation, new organisational forms of dwelling space, and new production technologies, as in the case of "on-demand" building systems production and the recently digitised "file-to-factory" routes.

The difficulty of long-term planning and the vertical, specialised and hierarchical integration inherent to modernisation is overcome through the adherence to the principles of reticular and horizontal aggregation of functions, decentralisation, and reduction of technological processing times and production cycles, whose characterising concepts become speed, flexibility, uncertainty, volatility planning [18]. Space-time compression, which characterises various aspects of contemporaneity, leads to the tendency to resize space according to the time variable, resulting in significant cultural consequences on the rarefaction of time and space as tangible dimensions of social life [19].

The new references progressively disengage from linear models. Still, the reorganisation of habitable space within reticular and circular processes opens a possible dividing line on the technique that Martin Heidegger had well perceived. It «is not, as is usually believed, an application of science but the soul, the essence of science, because science does not look at the world in order to contemplate it but to manipulate it, so the technical intention is already inscribed in the scientific gaze» [12]. The aspect of multiculturalism and multidisciplinarity in contemporary design research highlights the need to place the heuristic process of design activities on a level of overall understanding and intersectoral convergence of knowledge, overcoming the factors of the identity-based and hyper-specialist involution of knowledge that generates inequality and conflict [20].

Hyper-specialisation still represents the tendency of a technical character that induces the development of deep competencies but loses the critical sense of technique in its ethical and socio-economic interactions. Inhabiting and building evolved scenarios of society need a thought that can critically manage the choices and uses of technology in a design scenario capable of coherently integrating its contributions.

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INNOVATION AND KNOWLEDGE-BASED GROWTH FOR LOW CARBON TRANSITIONS IN THE BUILT ENVIRONMENT. CHALLENGES AND OPEN RESEARCH QUESTIONS

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Abstract

Humanity faces global challenges in climate change mitigation, water sustainability, and other areas. In order to address these challenges, radical innovation is needed to accelerate multiple "sustainability transitions" and create dynamism. Transitions research has focused on small niches and scales where empirical analysis can be done effectively. Niches and bottom-up initiatives for low carbon transitions in the built environment can help adjust policies and reconcile grand visions (top-down perspective) with ground implementation experiences (bottom-up perspective). Multiple factors can contribute to the creation of effective policies, and digitalisation and AI/ML applications, in the context of increasing automation, can be an opportunity to create new prosperity in a knowledge-based growth perspective, considering, however, the underlying critical assumptions, limitations and threats. Ten research questions deemed relevant for low carbon transitions from a bottom-up perspective have been proposed to generate multiple hypotheses for field testing.

Keywords

Sustainability transitions, Low carbon transitions, Innovation paradigms, Knowledge-based growth, Digitalisation, Built environment.

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1. INTRODUCTION

The United Nations (UN) initiative to achieve 17 Sustainable Development Goals (SDGs) and the increased focus on climate change agreements since the 21st Conference Of Parties (COP 21) in Paris in 2015 are just two examples of the growing awareness of the fundamental challenges that humanity is facing on a global scale regarding climate change mitigation, sustainable use of water, prevention of ecosystem degradation, reduction of waste production and disposal, reduction of poverty and inequality.

The ability to understand the dynamics of radical innovations and to combat inertia is at the heart of an emerging field of research dealing with "sustainability transitions" [1], which has brought an "agenda" to the attention of the research community [2] in recent years. From a socio-technical standpoint, the transition can be viewed as a "Great Reconfiguration" [3], in which the (quick) decline of existing technologies and services may coincide with the emergence of new ones at a rate never experienced before by humanity.

This "Great Reconfiguration" necessitates a horizontal and vertical integration of policy efforts towards "acceleration challenges" [4]. Horizontal integration due to the need to coordinate actions across different sectors of the economy (e.g. transport, energy, agriculture, etc.) and targeted cross-sectoral actions (e.g. education and fiscal policies); vertical integration due to the need to coordinate actions across scales, from international to national to regional and local initiatives. Both horizontal and vertical integration issues may delay acceleration in transitions.

The transition to a built environment with a low carbon footprint presents some peculiar aspects. The 6th Intergovernmental Panel on Climate Change Assessment Report [5] emphasises the importance of energy efficiency and renewables but also states that "sufficiency" – broadly defined as avoiding the demand for energy, materials, land, and water while delivering human well-being – has a crucial role in reducing greenhouse gas emissions. In order to reduce the carbon footprint of the built environment, "sufficiency" policies that decrease the need for new building spaces and make more efficient use of floor spaces in buildings will be crucial. For instance, "sufficiency" policies may consider dense and compact design, multi-functional spaces, shared spaces, and the repurposing of existing buildings as potential interventions.

The IPCC notes that behavioural change has the potential to decrease global emissions by 40 to 70 percent by 2050. Changes in lifestyle must occur on a systemic level throughout all facets of society. This includes, but is not limited to, increased recycling, decreased air travel, decreased meat consumption, and lowering thermostat temperature for heating. Motivation for behavioural change must be evaluated in accordance with socio-economic, awareness, risk perception contexts, etc. The persistence of behavioural changes will also represent a relevant problem to be monitored.

Closely related to the issue of behavioural change is the necessity of exploiting building efficiency and flexibility on a national scale to enable increased variable renewable-energy supply. Energy systems in numerous nations are undergoing rapid transformations as a result of increased renewable generation capacity. Grid decarbonisation through renewables is essential for low carbon transitions in the building sector (i.e., to decarbonise end-uses for heating, domestic hot water, etc.), but demand side policies are required as the increasing proportion of renewables necessitates a greater ability to adjust supply and demand balance dynamically (i.e. energy flexibility) to enable efficient and secure grid operation.

In this context, characterised by multiple concomitant changes, innovation models are especially relevant; for instance, the Quintuple Helix innovation model [6] is quite comprehensive and incorporates the aspects of academia, industry, government, civil society, and the environment. It is derived from the Quadruple Helix, and the helix (and perspective) of the "natural environments of society" is included. In turn, the Quadruple Helix added to the original Triple Helix innovation model vision (centred on academia-industry-government connections) a fourth helix representing the "media-based and culture-based public" and "civil society".

Already implicit in the original Triple Helix concept is the significance of higher education for innovation. On the one hand, the Triple Helix emphasises innovation and knowledge production in the economy; hence it is compatible with the concept of knowledge-based growth. On the other hand, the Quadruple Helix already promotes the knowledge society and democracy perspectives for knowledge production and innovation (by emphasising the role of "civil society").

According to the Quadruple Helix framework, the sustainable development of a knowledge economy involves co-evolution with the knowledge society. The Quintuple Helix emphasises the required socio-ecological transition of the twenty-first century's society and economy. Within the framework of the Quintuple Helix innovation model, the natural environments of society and the economy should also be considered drivers of knowledge creation and innovation, thus outlining opportunities for the knowledge economy (in multiple related research areas).

The underlying assumption of innovation models such as the Quintuple Helix model is that it is feasible to generate win-win conditions between ecology, knowledge, and innovation, hence building synergies between the economy, society, and democracy throughout socio-ecological transformations. Climate change is an ecological concern (substantiated by ample scientific evidence) to which innovation models should be used more effectively. A second essential assumption is that the (successful) exploitation of this potential could result in the formation of entrepreneurial ecosystems [7], which can have significant local and regional repercussions.

Increasingly, regions are viewed as eco-systemic aggregations of organisational and institutional entities or stakeholders with socio-technical, socio-economic, and sociopolitical conflicting, as well as converging (co-opetitive), goals, priorities, expectations, and behaviours, which they pursue through entrepreneurial development, exploration, exploitation, and deployment actions, reactions, and interactions. From a scientific standpoint, the proper conceptualisation of innovation ecosystems that are fractal, multi-level, multi-modal, multi-nodal, and multi-lateral arrangements of dynamic tangible and intangible assets is an incredibly difficult issue. Concurrently, there are several competing interests at stake.

Specifically, climate change and the financial and economic crises are bringing new difficulties on a global scale while also calling into question the quality of democracies. Detailing the relationship between the Green New Deal and the Quintuple Helix Model, Barth [8] examines this issue in great depth. In fact, the stagnant economic growth in established democracies, concurrent climate change and financial and economic crises, and the loss of biodiversity and depletion of resources all increase the risk of growing social disparity. These factors are already altering our daily lives and endangering the economy and the environment. Rethinking paradigms of innovation in light of accelerated change (transition) towards sustainability somehow becomes "the" present problem for humanity.

Progressive policymakers in developed democracies have hailed the "knowledge economy" and "knowledge-based growth" as a significant engine of future prosperity since the 1990s in reference to the multifaceted problem of knowledge. According to proponents, organisations and countries alike would flourish in the knowledge economy by nurturing knowledge from diverse viewpoints, so changing the emphasis away from capital investments, infrastructure, and machines, which dominated the "conventional" conception of capitalism. Even while manual labour and the goods and services it creates are not eliminated in the knowledge economy, their level of significance decreases. In principle, the role of "knowledge work" is that of increasing the efficiency of manual operations by introducing improved management practises or by automating some manual tasks.

In this paper, some of the assumptions of the "knowledge-based" growth paradigm are critiqued in regard to low carbon transitions for the built-environment, highlighting the mismatch between rhetoric and reality and proposing relevant research questions. While a high-level sketch of the problem of knowledge in relation to low carbon transitions is provided, which calls into question key assumptions of "knowledge-based" growth regimes, additional research is required to fully explore the future evolution of this concept in relation to breakthroughs in Artificial Intelligence (AI), Machine Learning (ML), and automation, as well as the effects these technologies may have on the global economy and environment. For this reason, in Section 2, key concepts needed to question "knowledge-based" growth paradigms are reported together with examples deemed relevant for their implication on the built environment. After that, in Section 3, the premises for the formulation of research questions in the broad area of "knowledge-based" growth in the built environment are reported; finally, 10 research questions are proposed in Section 3.3.

2. QUESTIONING THE ASSUMPTIONS OF KNOWLEDGE-BASED GROWTH IN LOW TRANSITIONS

The use of innovation models such as the previously mentioned Quintuple Helix [6] in a variety of situations demonstrates that policymakers continue to place a premium on knowledge-based growth. However, the mismatch between rhetoric and reality poses a concern, as it is obviously related to the danger of poor execution of policies supported by exaggerated expectations, arrogance, and insufficient understanding and conceptualisation of the underlying (multi-level) processes.

Since the focus is on growth [9], if the business models that are appropriate in the knowledge economy are capital-intensive tech corporations that require significant investment until they achieve market dominance, then education alone is unlikely to deliver social inclusion or competitive dynamism in and of itself. This is not intended to be a simplistic critique of education investment (how can we even conceive any type of human development [10] without carefully examining the dimension of education and knowledge growth?), but rather to identify pertinent research issues that must be considered when tackling the problem of accelerating knowledge creation and innovation in a setting of rising digitalisation and automation.

In the subsequent parts, the emphasis is placed on the identification of fundamental assumptions underlying the knowledge-based growth paradigm, the role of information and knowledge from science to policy, and, lastly, the issue of enhancing the public's understanding of the issues at stake (i.e. energy, environment and economy literacy). All of these factors are taken into account in an effort to provide a useful framework for identifying challenges and open research questions related to innovation and knowledge-based growth for low-carbon transitions in the built environment.

2.1. CRITICAL ASSUMPTIONS BEHIND THE KNOWLEDGE-BASED GROWTH PARADIGM

The fact that investment in education, deregulation of labour markets, increased financial rewards for entrepreneurs, and international openness could produce inclusive prosperity was an important aspect of the original knowledge economy's vision. In the past two decades, this vision has been challenged by issues such as business models, social inclusion, job polarisation, and conflicts between economic openness and regional development.

By starting from the problem of business models underlying knowledge-based growth, software companies were viewed as the ideal examples, but they were not the only type of business cited by proponents of the knowledge economy: financial services, creative industries, and science and engineering firms were also thought to have a high potential [11]. Unfortunately, the entry-level barriers in many of these cases are not as low as indicated by the theorists of knowledge-based growth, and businesses need to attract substantial capital investment to take these innovations through trial processes to market.

The assumed growth potential can be partially attributed to an idealised view of the digital industry in the 90s and to the business model of software companies in particular. In the software industry, a person who wishes to develop a new programme incurs minimal startup expenses, assuming they possess the necessary skills and have access to basic hardware. Manufacturing and distribution costs for digital products are negligible. Development costs for digital products are primarily comprised of their time.

Nonetheless, the evolution of business models in the Information and Communication Technology (ICT) industry has been substantial in the last two decades. In the case of Microsoft, the assets were intellectual property, and the advantage was determined by market dominance, at least in the beginning. They were selling a clearly defined product that was produced by the knowledge work of their employees, with near-zero marginal production and distribution costs once the product was ready for the market.

However, large tech companies such as Google and Facebook offer today their software services for free; they then sell market insights (to third parties) extracted algorithmically from users' interactions with their platforms, as well as advertising space on those platforms. This results in a shift in perspective as users, not employees (software programmers), become the primary assets. A large user base is essential for the creation of value for this type of business, and growing a large enough user base to make such a business model viable, constitutes a substantial entry barrier in the "new" digital economy.

In analogy to the ICT industry, the other types of businesses with a high potential for knowledge-based growth (e.g. engineering and science firms, creative industries, etc.) face difficulties when attempting to create economies of scale and network effects enjoyed by large tech companies. Financing emerging companies through lengthy periods of losses while they expand their user base calls for a substantial investment of capital. In analogy to what occurred in the software industry in the 90s, lowering the entry barriers for innovative businesses appears crucial for creating more dynamic conditions and stimulating business evolution through digitalisation across multiple sectors in a Quintuple Helix Framework.

However, how can these entry-level barriers be lowered when education, labour market flexibility, and increased financial incentives for entrepreneurial activities have not been sufficient to stimulate the market in recent years? In other words, if barriers to entry in the knowledge economy are higher than initially assumed, interventions such as public investment in education or tax cuts are unlikely to generate competitive dynamism on their own. This is a key point for reflection regarding the role of information and knowledge from science to policy and society, discussed in Section 2.2, and the role of literacy in data analytics in the energy and environmental sector, discussed in Section 2.3.

Another critical aspect of innovation from a policy-making perspective is its capacity to foster inclusiveness while fostering dynamism. One of the most alluring aspects of the knowledge economy (at least in its original vision) was its potential to facilitate social inclusion (defined as greater access to better work and concomitantly higher levels of material prosperity) via "social investment" in education and digital infrastructure.

The promise of an abundance of well-paid, highly-skilled jobs was essential to the marketability-based empowerment of workers and the appeal of the knowledge economy as a whole. However, the expectation that the knowledge economy will generate proportionally more new opportunities for better work and, therefore, that technological and economic change (i.e., innovation in Quintuple Helix Framework) will improve the lives of the vast majority of people has to be critically considered. From the perspective of the progressive case for the knowledge economy, what truly matters is whether the newly created work compensates workers adequately for the lost jobs.

This is discussed extensively by O'Donovan [12], who concentrates his attention on the problem of "automation anxiety" in our present economic landscape. Far from being a simple labour market problem, the coming wave of automation, described by different authors as a second machine age [13], a technological singularity [14], or a fourth industrial revolution [15], can result in equity and inclusion problems that can deeply affect society and threatens democracy.

In this context, the problem of "upskilling" becomes central as the knowledge economy did appear to offer workers the chance to move up the value chain and into more skill-intensive employment. These effects should be clearly monitored in time to ensure the limitation of the polarisation between new higher-skilled job opportunities and low-skilled, lower-paid roles and to prevent, to some extent, the disappearance of mid-skilled jobs while considering the issue of productivity.

The "upskilling" of workers is also relevant from the perspective of regional entrepreneurial ecosystems. According to the original knowledge economy vision, openness to globalisation was essential for countries to reap the benefits of knowledge-based growth. This allowed knowledge-intensive economies to export their innovative ideas and services to a variety of markets while importing the lower value-added physical goods and services they continued to consume. Additionally, economic openness facilitated the influx of talented workers, investment capital, and ideas, allowing knowledge-based companies to maintain and improve their global competitiveness.

Unsurprisingly, emerging economies have also prioritised investment in skills that enable them to compete at the top of global value chains, and increased interregional inequalities can mirror the previously mentioned risk of job polarisation due to the extremely uneven geographical distribution of high-skilled knowledge work that exists even in developed nations. This can exacerbate existing patterns of interregional inequality. In contrast, openness is currently threatened by critical factors such as geopolitical instability, which has an impact on energy and other vital commodities (such as raw materials), and by the impact of global supply chains on energy consumption and carbon emissions, which must be clearly accounted for in low carbon transitions. Understanding how business models can be implemented in the building sector and construction industry to overcome entry-level barriers and external factors, such as geopolitical instability, while simultaneously ensuring benefits and co-benefits (at the system level) is a major challenge in the energy transition.

2.2. THE ROLE OF INFORMATION AND KNOWLEDGE FROM SCIENCE TO POLICY AND SOCIETY

It is essential to begin with the issue of evidence when considering the role of information and knowledge in science, policy, and society. The evidence-based movement began with evidence-based medicine in the field of health. The scope of the movement was advocating for accountability in medicine based on a rigorous examination of which policies and practises were actually effective on the field. Experiment or trial concepts, and specifically the use of randomised controlled trials and systematic reviews of their results, are central to the evidence-based approach. While the initial emphasis on evidence-based programmes was primarily ethical, it led to criticisms related to the role of scientists on the one hand [16] and its technocratic stance and apparent neglect of power relations: «Policy-relevant facts are the result of an intensive and complex struggle for political and epistemic authority» [17], or to put it plainly, when «evidence-based policy become policy-based evidence». Indeed, an evidence-based policy can be used instrumentally to neutralise ideologies and to hide power asymmetries in decision-making processes.

A sceptical position regarding the role of science in policy action is the one by Collingridge and Reeve [18], which indicates two problematic assumptions regarding science-policy interaction:

1. policy action can be predicated on the accumulation of facts and the taming of uncertainty;
2. science has the power to provide dispassionate facts to adjudicate controversies.

The second assumption, in particular, is extremely interesting because the cases where science is called upon to adjudicate a policy appear to be associated with an escalating level of conflict, with opposing sides using scientific evidence to bolster their positions [19]. The definition of Post-Normal Science (PNS) proposed by Funtowicz and Ravetz in the 90s appears to be highly applicable to our present state condition. PNS is a novel approach to using science in situations where "facts are uncertain, values are contested, the stakes are high, and decisions are urgent". More extensively, the problem of the science crisis is analysed in detail by Benessia et al. in their book *Science on the Verge* [20].

Saltelli and Giampietro [21] clearly summarise the limitations of evidence-based policy, highlighting three relevant aspects. The first is the responsible use of quantitative information in quantitative storytelling, which proceeds primarily "via negativa" by falsifying the available options in terms of their feasibility (external constraints), viability (internal constraints), and desirability (compatibility with societal values). The second aspect, which is the one needed to test the salience and relevance of model-generated numbers, is the use of data and model appraisal strategies developed in the tradition of PNS, which are extensively reviewed by Carrozza [22] in a paper devoted to democratising expertise and environmental governance. The third key aspect is that quantification methods must maintain coherence across scales and dimensions (e.g., economic, demographic, energetic) when generating quantitative assessments with different metrics.

In this regard, while the Science of Science [23] transdisciplinary approach based on large data sets aims to study the mechanisms underlying the doing of science (e.g. choice of research problems, career trajectories and progress within a field) and to explain the underlying rationale, the pressure to publish, and the critical dimensions inherent to the definition of "impactful" science must be critically considered [24]. At the same time, new metrics, such as the ones proposed for open research [25], may be considered.

When referring back to the problem of science-policy interaction, the scholarly literature on science-policy interaction is typically divided between advocating that science and policy should be brought closer together or separated. However, Thoni and Livingston [26] found that science-policy practitioners were not as divided as the scholarly debate assumed them to be. They emphasise the importance of the discussion going beyond the relationship between science and policy and an unproductive battle between extremes. It is neither possible nor normatively desirable to demarcate "science", "policy", and other actors. While this discussion is of central importance to the actors of the Intergovernmental Panel on Climate Change (IPCC), greater emphasis should be placed on its relationship with society, where literacy could play a significant role, as discussed in Section 2.3, because we need to be able to capture the advantages (cost reduction, carbon emission reduction, etc.) and co-benefits (health, productivity, etc.) of re-inventing "efficiency" and encouraging "sufficiency" across several levels of society and built environment, exposing them transparently. This is deeply intertwined with quantitative storytelling.

The rigorous quantitative storytelling approach presented by Saltelli and Gianpietro [21] and discussed at the beginning of this section is highly related to the problem of critical thinking in the current debate around the interaction with society. This is discussed by Levitin [27] in *Weaponised Lies: How to Think Critically in the Post-Truth Era*, a reprint of *A Field Guide to Lies: Critical Thinking in the Information Age*. In a Post-Truth Era, the author proposes strategies to identify cognitive biases and logical fallacies and evaluate the credibility of information. The issues of recognising confirmation bias and belief perseverance, which lead to rash decisions and faulty reasoning, assessing the reliability of studies or surveys, and, for science and health news, searching for control groups and avoiding single-study results appear to be particularly pertinent today (especially after COVID-19 pandemic). In addition, the author cautions that "statistics are not facts"; numbers, statistics, charts, and graphs can (inadvertently or intentionally) be skewed to support particular viewpoints and should not be taken at face value. This can imply that people are susceptible to being "misled by numbers and logic".

Similarly, in the book *Weapons of math destruction: How Big Data Increases Inequality and Threatens Democracy* [28], O'Neil analyses how biases in the modelling process can lead to "automated" decisions that harm the poor, reinforce racism, and exacerbate inequality. Rather than being abstract, these problems are already experienced in numerous fields, such as insurance, advertising, education, and law enforcement. In light of these issues (already evident at the societal level), we must improve the data and statistical literacy level in the energy and environmental sectors, as will be discussed in the following section. This could contribute to the democratisation of science-policy-society interactions and stimulate new pathways for the knowledge-based growth illustrated in Section 2.1.

2.3. LITERACY REGARDING DATA ANALYTICS IN THE ENERGY AND ENVIRONMENTAL SECTOR

As described in Section 2.2, the use of mathematical modelling and indicators may create a false impression of precision but does not necessarily reveal "uncomfortable knowledge," which is typically avoided in policy discussions due to the potential for conflict. As proposed by [21], rigorous quantitative storytelling must be supported by accurate estimates, which can be achieved by making energy and environmental data more readily available in both open and synthetic forms. Regarding the built environment, digitalisation can improve the livability of cities in a number of areas, including healthcare and well-being, economic development and housing, engagement and community, management and operation of mobility, water, and energy infrastructures [29].

Open energy models and related data are crucial for promoting open research practises and fostering effective science-policy interaction [30]. By enhancing them compared to the current state of the art, for instance, they can promote multidisciplinary research that addresses the co-evolution of energy technology and human behaviour more transparently and, more generally, they can enhance the interaction of numerous linked models and data. Focusing on energy and environmental data in the built environment, the paper by Ahmad et al. [31] examines in depth the social, economic, environmental, and legislative drivers for the installation of metering technologies. While energy laws and regulations vary from country to country, there is a high level of technological standardisation and widespread use of advanced metering technology, which could serve as a basis for data collection at scale.

In light of the fact that the technology to collect energy data at scale already exists and that energy information is accessible (although not always easily accessible), it becomes possible to leverage literacy to make energy data understandable to a broad audience and facilitate change. This involves addressing the technological and social aspects of energy. In fact, researchers from a variety of fields are paying increasing attention to the concept of energy literacy. However, the energy literacy literature is characterised by a wide variety of definitions and techniques, making comparisons and the generalisability of results difficult. For example, Van den Broek et al. provide a classification framework for the numerous conceptual and practical approaches to household energy literacy [32]. Energy literacy is essential for informing people about their energy consumption habits and altering their mindset. As demonstrated by a number of studies, energy literacy encompasses not only the cognitive domain but also the affective and behavioural domains [33]. Essentially, it involves knowledge of technologies and devices, energy-saving actions, financial considerations, and other related factors. Better knowledge can pave the way for more innovative services and technologies [34], which must be evaluated from a whole life-cycle perspective, taking into account Life Cycle Assessment (LCA) and Life Cycle Cost (LCC). In conclusion, literacy is crucial to target behavioural change and make end-users behave rationally as prosumers (producers-consumers) in the future energy market, where greater investment in energy efficiency is needed.

3. OPEN RESEARCH QUESTIONS REGARDING LOW CARBON TRANSITIONS IN THE BUILT ENVIRONMENT

As described by Geels and Turnheim, low-carbon transitions in the built environment are part of a "Great Reconfiguration" (multi-level) process [3]. In order to meet IPCC-recommended environmental objectives, these transitions process must be accelerated. For this reason, innovation models are especially relevant today, and the Quintuple Helix innovation model [6], which includes the environment as the fifth helix, emphasises the problems of innovation to address sustainable development, including the problem of climate change.

Innovation models such as the Quintuple Helix model assume that creating win-win conditions between ecology, knowledge, and innovation is possible, thereby creating synergies between the economy, society, and democracy during socio-ecological transformations. It is believed that these transformations will have a significant impact on the knowledge society and knowledge economy. Thus, knowledge-based growth (e.g. growth for good [9]) is viewed as an opportunity to engage capitalism in the fight against climate catastrophe, thereby generating new employment opportunities.

As discussed in Section 2.1, this vision has been challenged over the past two decades by issues such as the evolution of business models, social inclusion, job polarisation, economic openness and regional development. While the knowledge dimension remains essential to innovation and fostering inclusiveness while promoting dynamism, the entry-level barriers in the knowledge economy are higher than initially thought. Policy interventions such as public investment in education or tax cuts are unlikely to generate competitive dynamism on their own. For this reason, Sections 2.2 and 2.3 discussed, respectively, the role of information and knowledge from science to policy and society and the significance of data analytics and literacy in the energy and environmental sector (as well as their economic implications).

This section aims to move from general considerations to specific issues to be addressed during the transition to a low-carbon built environment. In Section 3.1, some of the most pertinent global and local problems are summarised. In Section 3.2, issues of local innovation, productivity, and acceleration of low carbon transitions are discussed, and in Section 3.3, ten research questions are posed for field testing.

3.1. GLOBAL AND LOCAL SCALE PROBLEMS RELATED TO LOW CARBON TRANSITIONS IN THE BUILT ENVIRONMENT

The paper by [35] documents in detail global and local scale issues associated with low carbon transitions in the built environment, related to its present and future energy consumption, which are summarised below.

First of all, greenhouse gas Emissions and Global Climate Change: The building and construction sector accounted for about 39% of the process-related carbon dioxide emissions in 2018 [36]. Subject to the degree of the current and future decarbonisation of the building energy needs and of the power generation system capacity dedicated to buildings (which is almost 50% today), the building sector may be carbon neutral by 2050 or later, or may continue to be carbon intensive.

The second issue, future scenarios on the energy consumption of buildings, propose pathways to minimise the energy consumption of the sector by 2050 or later through intensive use of clean electricity and improved energy efficiency measures in buildings. However, such an objective requires the adoption of intensive green policies and a considerable increase in investments. No explicit engagements or even promises towards the adoption of such policies are undertaken, and there is a real risk that the energy consumption and the production of greenhouse gases in the building sector will continue to increase.

The third issue is the high global environmental impact. The building sector has a considerable impact on the global environment. The sector produces pollution and waste and consumes resources and raw materials. Future decarbonisation of the building sector is also associated with extensive additional use of raw materials. An increase in manufacturing efficiency, recycling, and adherence to the principles of the circular economy seems to be a reasonable policy; however, it is an open and difficult challenge for the construction sector.

The fourth issue is overpopulation and fast urbanisation. According to the United Nations [37], the world population may increase by up to 11 billion people by 2050, with most of the new population living in cities, increasing the urban population up to 6.5 billion people capacity of the building sector to meet the additional needs for new housing, commercial and community buildings and infrastructures.

The fifth issue is urban overheating and local climate change. Intensive urbanisation and industrialisation result in a considerable increase in the ambient temperature in cities. The phenomenon, known as Urban Heat Island (UHI), is well documented in many cities around the world. Higher urban temperatures have a severe effect on the energy consumption of urban buildings while impacting the environmental quality of cities, urban health and survivability levels. Therefore, the design and implementation of advanced mitigation and adaptation policies in cities are crucial.

The sixth issue is social inequalities, poverty and ethical issues. The provision of healthy and adequate shelter for everyone is a difficult challenge for the building sector when there are more than 1 million people living in slums, and the number is constantly increasing. In parallel, more than 150 million people in developed countries cannot afford to cover their basic energy needs. Eradication of poverty and energy poverty requires the implementation of generous, well-designed housing programs to enhance resilience in the corresponding countries and amortise social inequalities.

All the issues summarised above can have dramatic consequences on a global scale and are also extremely relevant for the future of the EU. The coordinated updating of existing policies together with well-targeted and innovative EU, national and local initiatives are required to deliver the required reductions of GHG emissions from buildings in Europe to nearly zero, as discussed by Norton et al. [38]. Three key aspects are identified in the paper: (1) ensuring that measures to reduce energy and GHG reductions also enhance the health and well-being of building occupants, (2) integrating decarbonisation of electricity and heat supplies for buildings with the decarbonisation of industry and transport, (3) reusing and recycling to reduce embodied GHG emissions in building materials, components and processes used in both the construction of new buildings and in building renovations.

The decarbonisation of buildings is an opportunity to develop new products and services that have the potential to create new high-skilled jobs, and this has clear political implications and can be incorporated into a more ambitious view of the transition pathways towards a low-carbon world [39]. Obviously, decoupling global economic growth from carbon emissions remains an open question. In this regard, Kaya Identity provides a useful method for analysing the similarities and differences between nations in their carbon intensity. Recent research by Bigerna and Polinori [40] social, and technological targets, such as continuous prosperity, growth, and increases in energy production and reductions in fossil fuel (FOS, for instance, demonstrates the convergence of the Kaya Identity components for the EU Member States towards the ambitious 2050 decarbonisation targets. Comparative Kaya Identity studies conducted on a global scale could provide valid evidence and insights that can aid in guiding policies toward long-term carbon reduction goals.

3.2. LOCAL INNOVATION, PRODUCTIVITY AND ACCELERATION OF LOW CARBON TRANSITIONS

While many sustainability challenges are global, as discussed in Section 3.1, the majority of transitions research has focused on the emergence of innovations in small niches and, in general, on a scale where the interactions between multiple "helixes" (e.g. in a Quintuple Helix innovation model) can be empirically analysed. Further, most of the studies regarding the acceleration of innovation have focused on the immediate technological and economic drivers of acceleration (e.g. R&D investment, upscaling, taxes and subsidies), while substantial policy and research efforts are needed to address "acceleration challenges" [4].

Addressing the "acceleration challenges" may require new governance structures and more active policies aimed at steering and orchestrating change: «Ensuring that socio-technical systems move towards greater sustainability is a major challenge for governments, but also for civil society. At the core of such transitions is a shift in governance structures that not only allows change to occur but also directs and orchestrates some of the changes» [41].

As stated in Section 3.1, simple interventions are unlikely to be sufficient to generate the necessary dynamism to promote the technological and behavioural change required for low-carbon transitions. The ability to effectively utilise data and insights from bottom-up initiatives and pilot projects to steer policies in a dynamic manner appears crucial. On the other hand, the technological potential of automation, utilising Artificial Intelligence (AI), Machine Learning (ML), and digitalisation, has only been partially exploited, and future scenarios are quite open and not necessarily constrained by pre-defined trajectories [42].

GATO [43], a highly adaptable artificial intelligence model (a "generalist agent" that can perform over 600 distinct tasks, like operating a robot, captioning images, detecting objects in pictures, etc.), was recently unveiled by DeepMind, a division of technology conglomerate Alphabet. We can honestly claim that there are few technologies that stir the imagination as AI does, and the hype around artificial general intelligence (AGI) is tangible. GATO is likely one of the most advanced artificial intelligence systems on the globe that is not dedicated to a particular function.

The idea that AGI, unlike traditional AI, will learn a task by intuition and experience, akin to a human, rather than requiring a large quantity of data to do so (being pre-trained or programmed to solve a certain set of issues), makes it very intriguing. Nonetheless, contemporary AI technologies combining supervised, unsupervised and reinforcement learning have quickly revolutionised the machine learning field leading already, for example, to generative AI applications such as ChatGPT by OpenAI, launched recently.

More modestly, we could say that while Artificial Intelligence (AI) is frequently manifested today in the form of complex deep neural networks, simpler Machine Learning (ML) techniques, whose inner workings are understandable, might be useful to tackle small- and medium-sized statistical, data mining and automation problems. Despite not being as fashionable as deep learning/AI, simple, reliable and scalable ML approaches can have a positive economic (as well environmental) impact (in a positive sense) in many applications where accurate predictions and decisions are crucial.

The fractal, multi-level nature of innovation and the fact that there are multiple transition pathways and specific low-carbon innovations to reduce emissions in each (sub)sector, which must be identified, designed, and managed, indicate a wide range of relevant (potential) applications for data-driven ML methods. As discussed in Section 2.1, the existing limitations with respect to business models, when there exists a relevant technical potential for savings, could be mitigated by simple and effective digitalisation strategies and ML applications could help lower the entry-level barrier to knowledge-based growth.

It is difficult to say whether AI/ML evolution will help overcome economic stagnation and create future jobs and prosperity through grassroots innovation (Phelps, 2014) while providing solutions to the problems discussed in Section 3.1. However, the challenge of maintaining technical innovation with a "human in the loop" approach to automation, fostering data analytics literacy and education rather than merely stoking technology hype cycles [44], is definitely worth attention.

In recent years, there has been a proliferation of artificial intelligence (AI) strategies designed by different countries to maximise benefits while minimising risks. As indicated in comparative studies, the policy is fundamental, and the differences between, for instance, the EU and US are significant [45]there has been a proliferation of artificial intelligence (AI. Simultaneously, numerous organisations have launched a vast array of initiatives to establish ethical principles for the adoption of socially advantageous AI. Also in this instance, the proliferation of principles threatens to overwhelm and confound.

The problem is analysed by Floridi and Cowls [46], who propose five core principles to synthesise the plethora of emergent instances in this research field. To simplify as much as possible, four of them are fundamental bioethical principles: beneficence, nonmaleficence, autonomy, and justice. The fifth principle (specific to AI) is explicability, which includes both intelligibility (as an answer to the question "how does it work?") and accountability (as an answer to the question "who is responsible for the way it works?") in the epistemological and ethical senses, respectively.

Far from being generic, Floridi and Cowls' principle of "explicability" requires a clear commitment to the creation of AI/ML applications and technical aspects such as "explainability" (i.e. the extent to which the internal mechanics of a machine-learning algorithm can be explained in human terms) and "interpretability" (i.e. the extent to which a human can understand the rationale behind model output, given a change in input, and the algorithmic logic can be quickly inspected) are called into question. These two technical factors are essential to guarantee the possibility of inspecting, auditing and trusting the AI/ML model, contributing (at least partially) to minimise the risks outlined in Section 2.2.

This ethical dimension of AI/ML has direct implications for the construction industry in the context of increasing digitalisation. Emerging technological solutions for the digitalisation of design and construction processes, digitalisation of the supply chain of the construction industry, predictive control of energy demand, predictive maintenance of construction technologies, peer-to-peer energy trading within energy communities, and many other possible applications are heavily dependent on data-driven (AI/ML) models.

For this reason, the "explicability" principle must be considered (due to the use of AI/ML models) alongside the other decision-making principles discussed in Section 2.2: feasibility (e.g., external constraints determined by the use of natural resources [47]), viability (internal constraints, specific project factors), and desirability (e.g. compatibility with societal values, closely linked to behavioural change issue). At the same time, literacy can improve comprehension of new technologies and their effects and promote social acceptability and desirability for the wider public.

3.3. OPEN RESEARCH QUESTIONS RELATED TO INNOVATION AND KNOWLEDGE-BASED GROWTH

The growing awareness of the fundamental challenges humanity faces on a global scale, including climate change mitigation, the prevention of ecosystem degradation, and other major problems, necessitates an acceleration of innovation-supporting policies, as already discussed. The ability to grasp the dynamics of radical breakthroughs and to fight inertia is at the centre of a growing field of research dealing with "sustainable transitions" and "low carbon transitions" are part of it.

Most transition research has focused on the emergence of innovations in small niches and, in general, on scales where empirical analysis can be conducted effectively on the ground. As seen in Section 3.1, global scale problems associated with low carbon transitions for the built environment have direct (and frequently dramatic) implications at the local scale, and it is necessary to reconcile the grand visions (i.e. the top-down perspective) surrounding the aforementioned challenges with the implementation experiences on the ground (i.e. the bottom-up perspective).

The applications enabled by digitalisation and AI/ML techniques could, in principle, align (at least partially) with the benign vision of knowledge-based growth, whose critical assumptions and limitations were analysed in Section 2.1. Nonetheless, multiple technical and ethical issues must be considered, and ten research questions, deemed pertinent from a bottom-up perspective, are posed hereafter:

1. Are business models for knowledge-based growth appropriate for low carbon transitions in the built environment (e.g., are mechanisms and indicators used in decision-making processes fit for purpose, particularly in a long-term, whole life-cycle perspective?)?
2. Are accounting methods used transparently from a system perspective (e.g., do they consider the

potential shifting of impacts from one system to another?)?
3. Is the human dimension considered and correctly accounted for (e.g., all the aspects connected to behavioural change, which may have direct and indirect impacts on carbon emission)?
4. Are uncertainty and risk dimensions accounted for properly (e.g., in relation to energy pricing dynamics, behavioural change, etc.)?
5. Are low carbon transitions promoting innovation, digitalisation, productivity and competitiveness (i.e. do they actually foster innovation compared to the state-of-the-art? How can we measure it?)?
6. Is AI/ML "digital twin" paradigm suitable for low carbon transitions in the built environment (e.g. how can we design systems of interconnected AI/ML models able to deal with the multiplicity of aspects involved?)?
7. Are ethical principles considered with respect to digitalisation, automation and AI/ML use in projects?
8. Are literacy and analytics changing the perspectives in decision-making processes, or are other contingent factors more influential?
9. What job opportunities are generated in the low carbon transitions in the built environment, and is job polarisation a relevant problem?
10. What can be the role of small-scale projects in promoting skills development and regional ecosystems of innovation from a globalisation perspective?

These questions can be expanded upon and can lead to the formulation of hypotheses that can be then tested on the ground in small niches and bottom-up projects (for the reasons outlined previously), which can, in turn, generate policy-relevant insights if experiments are appropriately conducted, and research data is made available in open and accessible formats.

4. CONCLUSION

The fundamental challenges humanity faces on a global scale regarding climate change mitigation, sustainable water use, prevention of ecosystem degradation, reduction of waste production and disposal, and regenerative agriculture are the focus of "sustainability transitions" [1] research. Transition processes can be considered a "Great Reconfiguration" from a socio-technical perspective [3]. A "Great Reconfiguration" requires horizontal and vertical policy efforts to accelerate innovation policies under new inexperienced conditions. Socio-technical change can be seen as an opportunity for radical innovation (as part of paradigms like Quintuple Helix) and for entrepreneurial ecosystems at the local and regional levels.

One of the underlying assumptions in innovation paradigms such as Quintuple Helix is that knowledge-based growth can bring several advantages. Some of the "automatic" presuppositions behind innovation paradigms have been critically analysed in Section 3.1, and the problematic science-policy-society interaction and tensions have been discussed in Section 3.2 in relation to the development of policies. Addressing these tensions and increasing the level of literacy regarding energy and environmental themes (as well as their economic implications) appears crucial today, as indicated in Section 3.3, together with initiatives nudging behavioural changes, which may have a fundamental impact on low carbon transitions.

Further, traditionally innovation policies have focused on the immediate technological and economic drivers of acceleration (e.g. R&D investment, upscaling, taxes and subsidies). However, "traditional" policies are unlikely to deliver prosperity, social inclusion and competitive dynamism in and of themselves in a knowledge economy. Further, sustainability transitions research has focused on small niches and scales where empirical analysis can be done effectively. Insights from niches and bottom-up initiatives for low carbon transitions in the built environment can help adjust policies quickly and reconcile grand visions (top-down perspective) with ground implementation experiences (bottom-up perspective).

On the one hand, multiple factors can contribute to the creation of effective policies, including rethinking the role of information and knowledge from science to policy and society (i.e. science-policy-society interaction in a knowledge society) to promote literacy. On the other hand, digitalisation and AI/ML applications, in the context of increasing automation, can be an opportunity to create new prosperity in a knowledge-based growth perspective, acknowledging opportunities and threats. Emerging technological solutions for the digitalisation of design and construction processes, digitalisation of the supply chain of the construction industry, predictive control of energy demand, predictive maintenance of construction technologies, peer-to-peer energy trading within energy communities, and many other possible applications are relying heavily on data-driven (AI/ML) models.

Far from being a generic instance, Floridi and Cowls' ethical principle of "explicability" [46] implies a serious commitment in relation to "explainability" and "interpretability". These two technical aspects are essential to guarantee the possibility of inspecting, auditing and trusting AI/ML algorithmic logic and models, making them more "transparent" and contributing, at least partially, to reduce the risks of their application.

Considering ground implementation experiences, multiple research questions can be formulated, involving, for example, how business models are conceived (e.g., are decision-making mechanisms and indicators fit for purpose, especially in a long-term, whole life cycle perspective?) and what are the state-of-the-art advances (are digitalisation, productivity, and competitiveness dimensions addressed?) determined by low carbon transitions. Quantification of uncertainty and risk, transparency of modelling strategies, and suitability of AI/ML-based paradigms like "digital twins" are also crucial issues in combination with human factors.

Finally, Section 3.3 research questions aim to stimulate the development of hypotheses that can be tested in small niches and bottom-up projects, which can, in turn, generate policy-relevant insights if experiments are appropriately conducted and research data made available in open and accessible formats. Creating a knowledge society in a knowledge economy and promoting knowledge-based base growth strategies require targeted and thought efforts rather than grand visions inflated by rhetoric and hubris.

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COVID-19, DESIGN AND SOCIAL NEEDS: AN INVESTIGATION OF EMERGING ISSUES

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Abstract

The global public health crisis generated by the spread of COVID-19 has revealed – and is still showing – the strong correlation between two apparently disparate fields of research: built environment and health. Although in this time of emergency, the science of architecture could offer a remarkable contribution to rethinking new living and working spaces, the ongoing pandemic has, in terms of people's well-being, disclosed the weaknesses of a vast number of architectural design choices implemented until now. Hence, the impact of the COVID-19 pandemic on the users' space fulfilment has been herein explored and analysed through a systematic literature review process for collecting data and exploring gaps and opportunities revealed in this period. The COVID-19 pandemic and especially the quarantine constrictions have revealed a high level of dissatisfaction with the quality of living space as well as the lack of flexibility and adaptability. This study has outlined the main critical aspects to be considered for shaping and re-building new ways of living in a post-COVID-19 society. Thus, rather than focusing on specific future solutions, this study aims to collect the main issues and planning opportunities by showing the need for a valuable transdisciplinary approach that could address people's demands, especially from a sociological, anthropological, psychological and health perspective.

Keywords

COVID-19, Quality living, Built environment, Architecture, Well-being.

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1. INTRODUCTION

On March 9, 2020, the Italian Government signed an Executive Order that has marked the history of the Country: Article 1, Paragraph 1 of the DPCM introduced restrictive measures against the spread of the COVID-19 virus, starting from bans on travelling and restrictions on leaving home without proven work requirements, situations of need and/or health reasons. China, the heart of the pandemic, first adopted the restrictions (23-28 January 2020) that were afterwards introduced worldwide through National Government orders. A slogan such as "stay at home" was used in different languages to invite people to contain the spread of the pandemic. Moreover, schools, universities, offices, retail as well as commercial activities were closed due to the increase in deaths and the rapid and unstoppable transmission. Consequently, people have been forced to stay home and reduce public space use in lockdown conditions by reinventing themselves and their available spaces for different and unforeseen functions. People dealt with the importance of the quality of life as it concerns their house and its spaces, their interior design, together with neighbourhood, city, streets and so forth. This unprecedented and unexpected set of conditions has caused professionals such as architects, engineers, planners, and designers to rethink spaces by offering suggestions for the future development of new spaces.

However, the debate on the re-shaping of cities and houses has divided into two different categories: the first is related to the idea that everything will not be the same and the design thinking should be reconsidered completely; the second is that everything will come back to normality. On the one hand, solutions for liveable spaces with physical distancing precautions as well as the introduction of new design approaches that take into account flexibility, have been proposed. On the other hand, the temporariness of this current pandemic situation has been pointed out by outlining that, even if we live in unique conditions, by adopting the business-as-usual approach, everything will return to normal sooner or later. At the time of writing, approximately two years after the diffusion of the pandemic, it is difficult to say who is right, even if this can, in fact, be traced. It is interesting to highlight how the pandemic forced us to reflect on high-quality living and the fairness of the historical design choices adopted to date. Houses, once considered merely places to sleep, are now places to live all day: they have, in fact, been jammed with all family members, becoming, by necessity, offices, gyms, schools, restaurants, places of recreation and so on. Public spaces (such as roads, streets, and squares) and semi-public spaces (retail, offices, and businesses) have been emptied and used just for purposes of necessity. All of this has contributed to an ever-growing acquired consciousness of the importance of the living quality for users and inhabitants, better defining what they want and especially what they do not want for their spaces. For example, there is a shared recognition of the significance of green spaces with the proven correlation between their use and benefits for physical/mental health. The exploration of peer-reviewed articles has provided other fundamental insights into what high-quality living means, especially after the outbreak of the COVID-19 pandemic. This paper offers a point of view on the theme by collecting and analysing peer literature reviews to provide initial documentation, which this study of the emerging factors of the COVID-19 impact brings to light, and where the adopted solutions of planning and design have failed.

2. METHODOLOGY

In order to analyse how and to what extent COVID-19 restrictions impacted the research on the built environment and its related issues, a systematic literature review process has been conducted involving peer-reviewed article journals and conference proceedings. The state of art methodology (Fig. 1) has been based on the research method of Content Analysis, which determines the presence of certain words, themes, or concepts within some given qualitative data (i.e., text). Using content analysis, researchers can quantify and analyse the presence, meanings and relationships of certain words, themes, or concepts in a predefined domain of interest. There are two general types of content analysis: conceptual and relational. The first determines the existence and frequency of concepts in a text, while the second develops the conceptual analysis by examining the relationships among concepts in a text.

No matter the chosen method, the analysis process reduces the volume of text collected, identifies and groups categories together and seeks some understanding of it. The presented research has been carried out by using Conceptual Analysis and, according to the standardised research process, it has been developed in three main steps, each of which is subdivided into sub-sections:

- research's definition with (1.1) related area delimitation and (1.2) keywords' search identification;
- data collection of articles within the research's scope with (2.1) literature search through selected databases corresponding to the total amount of reached articles, (2.2) limitation of articles in the field of interests, namely: the first level of screening, limitation of essays depending on publication type and language; the second level of screening (2.3) selection of articles related to chosen keywords; the third level of screening, with subsequent three levels of screening and selection (Tab. 1);

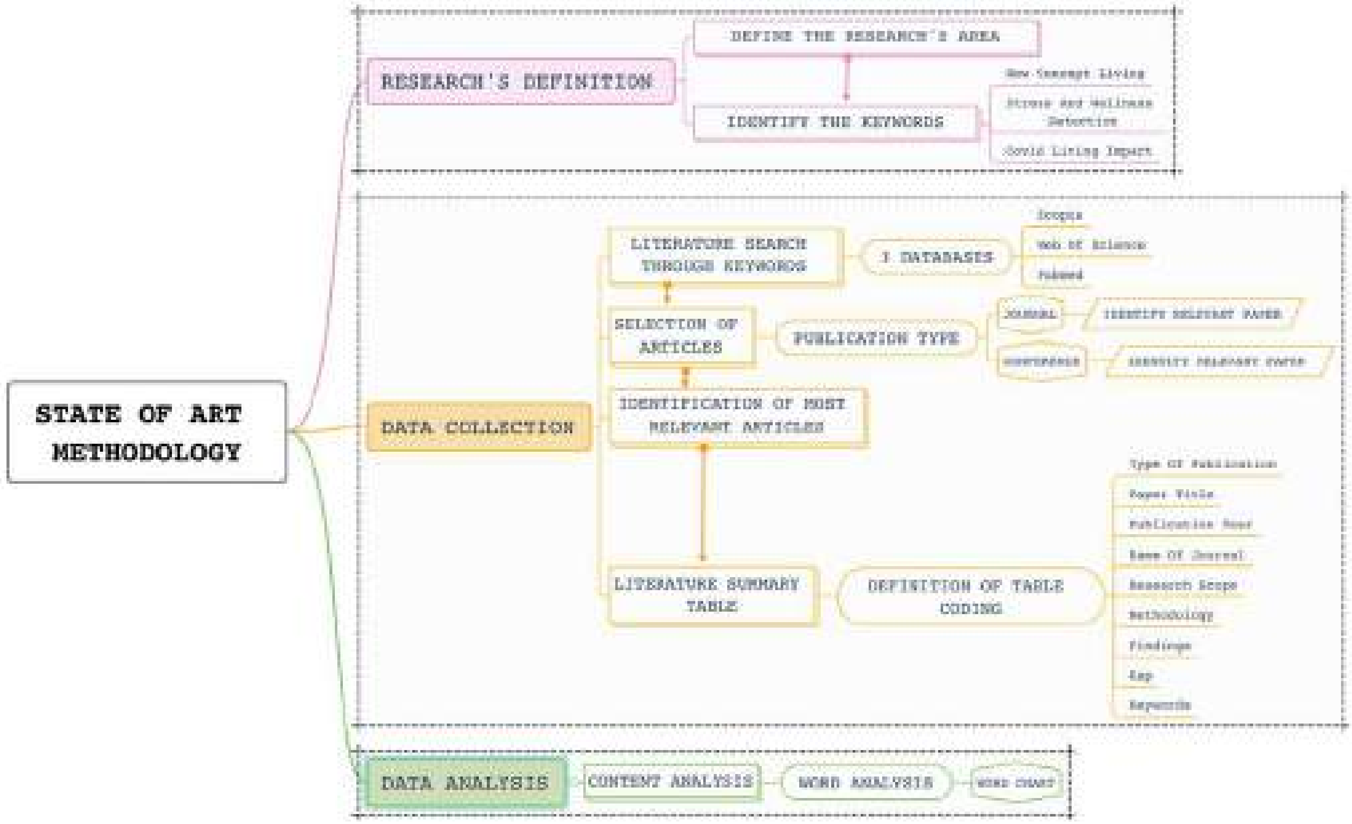

Fig. 1. *State of Art Methodology.*

- data analysis through word analysis and (3.1) word analysis of databases results and (3.2) word analysis of selected articles.

The research definition has first been conducted by delimiting the research's area of interest, namely the impact of COVID-19 on the perception of the built environment, and second by identifying related keywords. Therefore, the search has been conducted through the following systems: "TITLE (COVID-19) or (Covid) or (pandemic) and TITLE (architecture) or ('built environment') or ('living space') or (living)". The second step of the state of art methodology consists of data collection, with the selection of databases, the limitation of articles and the selection of targeted articles. Three academic databases have been screened for literature review: Web of Science [1], Scopus [2] and EBSCO [3]. This choice guaranteed a broad coverage of the theme in the field of the built environment, architecture, design, engineering, and sociology. Thus, the research has been confined to peer-reviewed articles and conference proceedings written in English and Italian.

The targeted selection of articles concerned three main screenings and depends on the field's consistency, such as the theme's congruence and consistency after the abstract as well as the full article's reading. Finally, careful data analysis has been carried out through words and content analysis. A first-word analysis was made on the main results obtained through specific databases, thanks to the use of Vos Viewer Software [4]. A second-word analysis of selected targeted articles was made through Voyant Tools. The content analysis has involved the outline of the main impacted and discussed fields and the related prominent issues.

As shown in the following Table 1, a total number of 419 articles were found, and after the above-mentioned screening and the elimination of 22 repetitions, 49 papers have been deeply analysed.

Database	Total	Total after 1st screening	Total after 2nd screening	Total after 3rd screening
WoS	141	71	36	18
Scopus	223	110	19	15
Ebsco	55	54	22	16
Total	419	235	77	49

Tab. 1. *The total number of reviewed articles.*

3. RESULTS

This chapter discusses the data of the literature review of the screened articles. Results are divided into Word Analysis and Content Analysis to give a clear view of the theme. Word analysis has been conducted on 235 articles available on the three chosen databases and associated with articles selected after the first screening related to the consistency of the field. This choice has been pursued both due to tool rules that, in fact, allow detecting keywords directly from database history and, moreover, for research approach reasons. Although not explicitly related to the impact of COVID-19 on the built environment but generally concerned with the search system "TITLE (COVID-19) or (COVID) or (pandemic) and TITLE (architecture) or ('built environment') or ('living space') or (living)" in the selected field, it is interesting to note the main keywords referred to the screened articles. Subsequently, a restricted area of the 49 selected papers on the theme has been analysed to give a specific overview of the theme in their contents.

3.1. WORD ANALYSIS

Word analysis from articles has been used to present the frequency of different keywords over the same theme. The content analysis in the related field of interest has been done by investigating the three selected databases: Web of Science, Scopus and EBSCO. Word frequency analysis was detected within the titles, and the abstract was then analysed through Vos Viewer Software.

Fig. 2 shows the words most used in articles collected on Web of Science. As it is graphically depicted, the most frequently used expressions related to the connection between Covid and the built environment are related to green space, health, mental health, nature, experience, solution, concept, perception, infection, and information. Fig. 3 represents the same procedure in Scopus with the following most common words: experience, need, concept, green space, mental health, social distancing, restrictions, infections, survey, and experience.

On the other hand, Fig. 4 provides the most used words in EBSCO: space, covid, pandemic, author, social

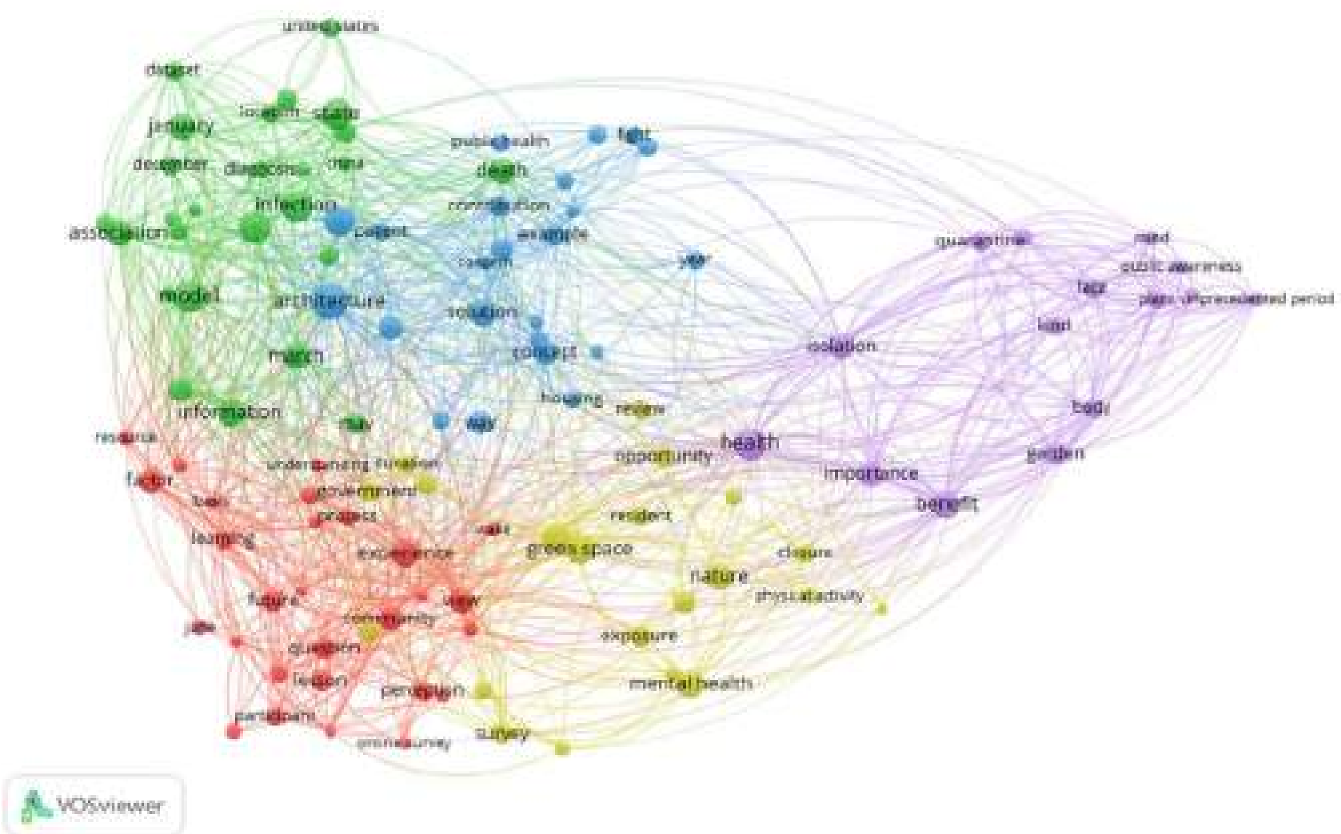

Fig. 2. *Word analysis in Web of Science Database by using VOS viewer.*

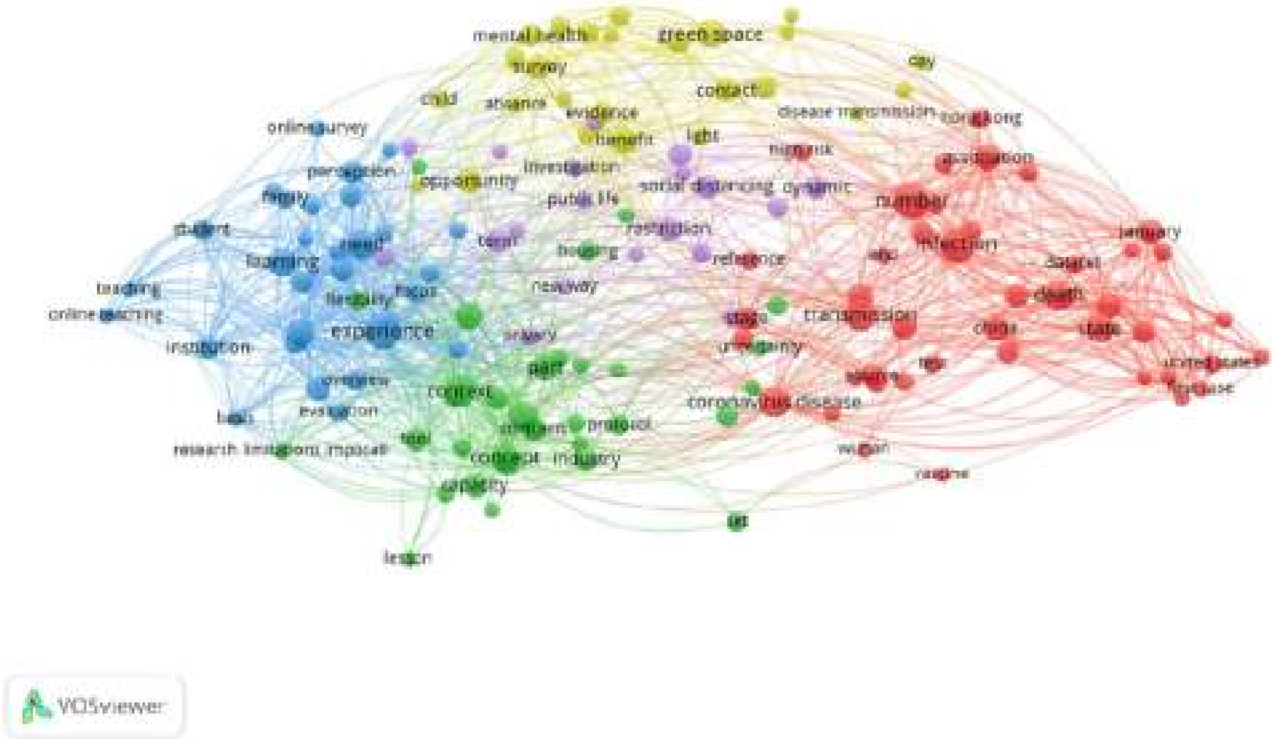

Fig. 3. *Word analysis in Scopus Database by using VOS viewer.*

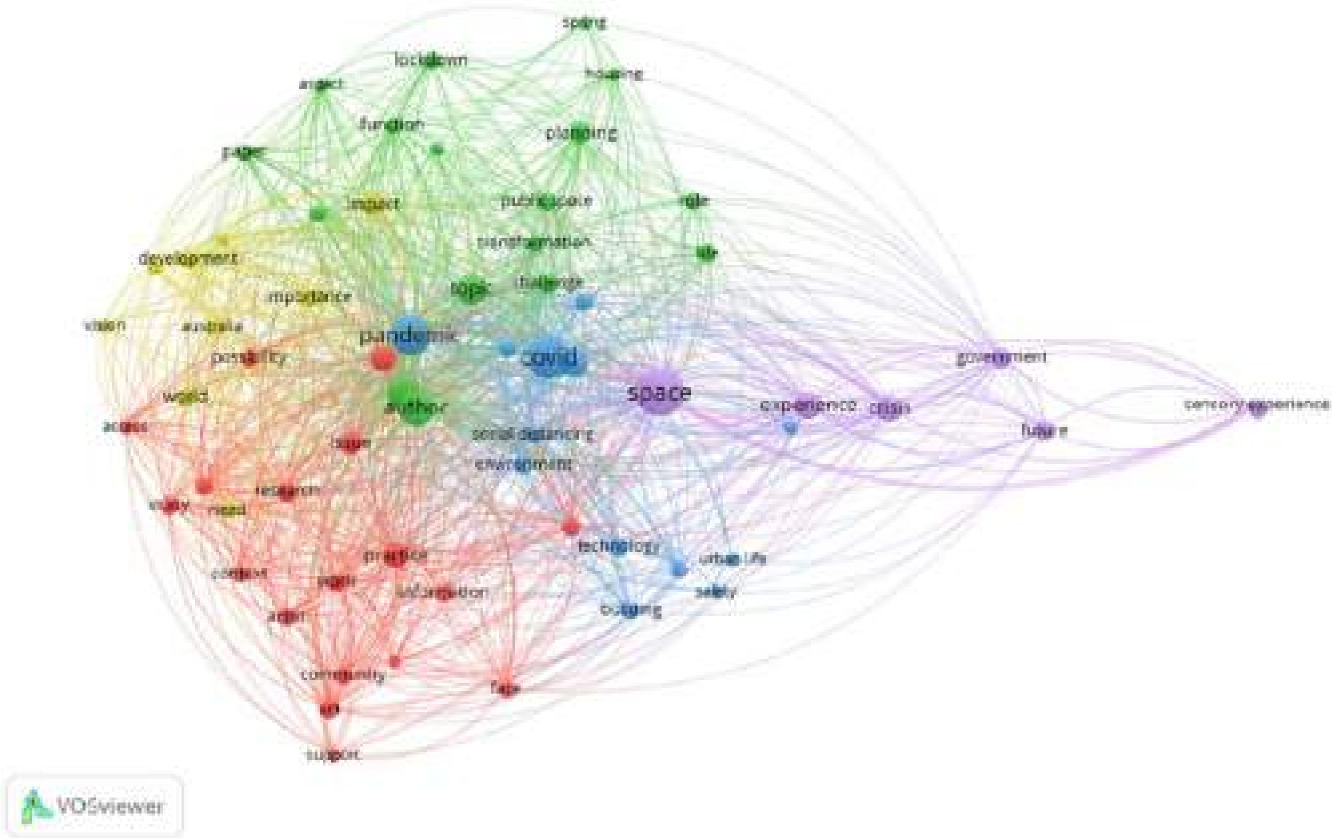

Fig. 4. *Word analysis in EBSCO Database by using VOS viewer.*

Fig. 5. *Word analysis and keywords detection through Voyant Tool.*

Fig. 6. *World analysis and empirical content keywords through Voyant Tool.*

distancing, environment, housing, community, crisis, and challenge. Thus, usual terms such as green space, health, mental health, concept, and perception cover the search topic more frequently. Overall, this analysis shows how the main keywords related to the impact of COVID-19 on the built environment focus more on health/mental health/experience rather than on planning design choices. Consequently, when considering that users' experiences should be a core topic of the architectural investigation interests, the social and psychological role of the built environment emerged.

Another content analysis was carried out by considering the authors' and empirical content analysis keywords of the 49 selected articles, again using Voyant Tool Software. Regarding what has been said, Figure 5 and Figure 6 show the results. It appears that the most frequently used words deal with the theme of architecture, space, urban, covid, pandemic, public, green space, health, quality, and resilience, confirming that besides the keywords rightly used for finding purposes. The focus on social and psychological aspects has been confirmed by the theme's definition (such as covid, pandemic, architecture and so on). The following section discusses how the built environment has been intended in the foundation articles and the main related aspects of relevance in terms of the COVID-19 impact.

3.2. CONTENT ANALYSIS

In all research, it is essential to begin by clarifying what the researcher wants to discover, from whom and how. The purpose may be of a descriptive or exploratory nature based on inductive or deductive reasoning. Inductive reasoning is the process of developing conclusions from collected data by interweaving it with new information. The researcher analyses the text with an open mind to identify meaningful subjects to answer the research question. Deductive reasoning proceeds in an opposite but logical way that moves from multiple premises – generally assumed to be true – to a conclusion. Due to the idea of the authors to identify future research lines based on a systematic investigation, the adoption of inductive reasoning has been used. The results are presented in this paragraph. Figure 7 graphically depicts the results of the main impacted spaces and related issues due to COVID-19.

Five space variables and their main issues were identified, indicating the main topics to focus on. As shown in Fig. 7, the identified peer-reviewed articles and conference proceedings concentrate mainly on public spaces, green spaces, city, interior design/home and generically built environments. Regarding this last aspect, the evaluation of the COVID-19 impact has generally been considered by authors at a different scale, starting from the design scale and progressing to urbanism. In all scales of the Built Environment, social inequalities have been pointed out by locating the correlation between financial difficulties and dramatic inequalities that exist among the spaces in which we live [5–8].

Following this aspect, it is crucial to highlight the association between inadequate spaces and mental health issues, especially concerning poor-quality views and in-

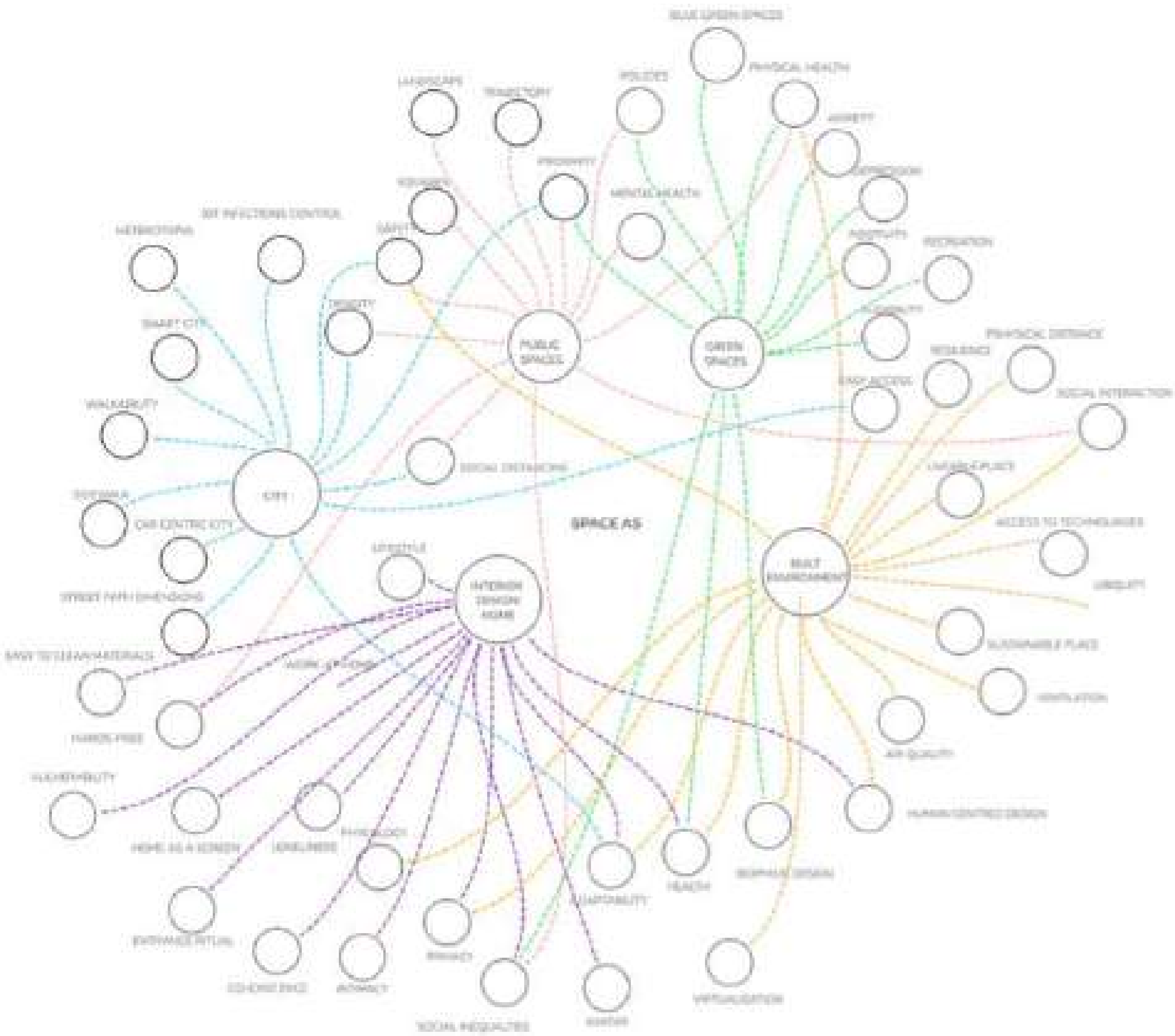

Fig. 7. *Topic issues due to COVID-19's impact on life.*

door areas that cause depressive symptoms [9]. On the other hand, fewer symptoms of depression and anxiety have been demonstrated when inhabitants can access a garden or simply view nature [10]. Consequently, the correlation between mental health and the built environment has a primary place [11, 12].

4. DISCUSSION

This paper finds that architecture has been under discussion due to the weak reaction to an unforeseen event such as COVID-19, revealed in a lack of flexibility and adaptation. This points to such fragile planning that mental, physical, and psychological health issues of users have become the subject of significant debate by design professionals. In other words, COVID-19 brings to light a pre-existing problem not clearly disclosed until that moment: the planning's current lack of resilience and its rupture with a strategy based on one's health.

However, if, on the one hand, the role of architectural practice to respond to living needs appears to have failed, on the other hand, the determination to shape, invent, and re-build new ways of living in a post-COVID-19 society is preeminent. It should be based precisely on socio-spatial non-fulfilment. As such, this section offers insights into various design liabilities according to the five planned spaces under investigation in this study: built environment, green space, public space, the city and design/home.

4.1. BUILT ENVIRONMENT

The authors have analysed the importance of health spaces at different scales. As reported by Fezi [13], who outlined how the impact of COVID-19 on the built environment is related to object scale (among others) with the related issues of hygiene; people scale with distancing and isolation; cities and transportation with proximity, downscaling and mobility. According to Pinheiro [14], historical pandemics such as the Black Death, cholera, and tuberculosis have changed the design by moving thinking forward to minimalist design. However, in the case of the COVID-19 outbreak, one of the main aspects upon which we should reflect is the temporary positive effects on the environment, with a win-to-win relationship between nature, breath (fresh air) and the safeguarding of health. Other studies have been conducted to highlight the association of built environments with the spread of COVID-19 [15] with the aim to adopt new design strategies, starting from air quality improvement systems [16] or rediscovering both for health and social reasons, filtering the air in areas such as courtyards, balconies, stairs, condominium terraces [17].

By saying it with the words of Keenan [18, p. 219], we should "learn from disasters" and try to understand what is working and what is not in the face of this unique situation. Other main issues of the built environment relate to privacy, adaptability, virtualisation and social interaction. Thus, the built environment should be considered a space that should help us live in a healthier way [21] by reconsidering the evaluability and liveability of places. A transdisciplinary approach that covers unrelated fields is needed, but as COVID-19 has demonstrated, such as psychology, sociology, medicine and so on, are not so.

4.2. INTERIOR DESIGN/HOMES

Pertinent issues, both in the generic built environment and interior design/home, have emerged: adaptability, privacy and virtualisation. Privacy has become a relevant theme during the lockdown. Privacy concerns both real and virtual spaces since the isolation brought about enforced intimacy [19]. At the same time, spaces are displayed through virtualisation and private surroundings have been indicated by demonstrating the boundaries between public and private life [20, 21]. According to Porcelloni [20], the inevitable online exhibition of personal space prompted people to show as little as possible of their homes due to the perception of the equivalence between private life/house and what is revealed by the screen. It is also interesting to note, even in the space of virtualisation, the mixed-use of domestic spaces which host different activities connected with education (remote school), productive activities (remote work) and so on [22], due to their new multiple functions (gym, office, leisure, education and so on) that require adaptability and flexibility [19]. The lack of privacy is a sensitive subject connected to the consequences of the lockdown measures, not only in terms of the public-private sphere but also in terms of the co-existence of different family members in the same place/space [23].

House is required to host more functions and contemporary users within the same place. For this reason, as reported by Madeddu [24], the preeminent higher quality of living required today is also indicated by the housing market. The question in evaluating a house today asks: could people face living in that same location if lockdown occurs again? Finally, by strongly showing a preference for homes with hands-free contact and easy-to-clean materials [14], the house has now been considered a safe place to shelter. For this reason, it has become a kind of holy place that sometimes has resulted in an "entrance ritual" [20, p. 641] with specific procedures such as taking off shoes, washing hands, changing clothes and so on.

Other relevant aspects, such as the correlation between house and perceptions of loneliness, conditions of vulnerability, psychological problems and health issues, emerged.

4.3. CITIES

Cities have had a crucial role to play in virus transmission and shutdown. For this reason, the debate on the relationship between cities and COVID-19 has been discussed, focusing on the main emerging issues. According to Mazzolini [25, p. 23], «each city manages covid emergency based on physical and conceptual [sic] specific to it», and this has led to the discussion of the main uncovered issues in city planning. High-density space in cities is undoubtedly a central problem that, by replacing the car-centric city concept [25], flowed into the consequent reclaiming of the streets for people and nature. Another relevant term teamed with the idea of the city is "smart city", "IoT city", with the use of new technologies to improve citizens' lives with health and safety purposes in mind: IoT infection controls [26].

4.4. GREEN SPACE

The most frequently discussed argument, regardless of the specific planning area, is the significance of green spaces. Nature has been considered the most crucial aspect to refer to during planning, especially after COVID-19's impact on people's perceptions, whether for housing views, the redesign of public spaces or other purposes within the city's projects.

Nature, also called "blue-green space," is sought for its positive effects on mental health as well as for the reduction of anxiety and depression [27], better physical health, relaxation [28], and as a recreation place [29]. The demand for green spaces has also been measured through Sina-microblog analysis [30] or a specific case study like in Oslo [29]. However, probably more than in any other field, green spaces represent current social inequalities through the inability of all to privately enjoy them because of financial difficulties [8]. Since the green-blue space generates well-being and maximises health, this aspect merges with the following public space issues.

4.5. PUBLIC SPACE

Public spaces seem to be the most impacted places due to the restrictions of social distancing and the reduction of leisure activities. Among others, the impact of COVID-19 on the design of public spaces has been mainly discussed in terms of inclusivity, accessibility and proximity [7, 31–33]. For this reason, the study of possible best practices of public space design has been reported through the analysis of cities as case studies (such as Roma, Siena, and San Benedetto del Tronto [31]), to understand how we should rethink public space in times of the pandemic. Streets, squares and, more generally, areas for the community have been reviewed for design optimisation: walkability, proximity, easy access, and social inequalities have become the main key points [32–34].

In times when social distancing (actually physical distance) is required to prevent COVID-19 transmission, proximity and short walking distances are needed. Thus, the design of public spaces should be reconsidered by taking into account the importance of community by guaranteeing easy access to services as well as wider spaces and the careful analysis of the trajectory of flows [35–37]. Moreover, for a higher quality of life and mental/physical health benefits [38], the proximity and flexibility of public spaces are mainly required in terms of green areas.

5. CONCLUSION

This study provides outcomes on the impacts of COVID-19 on public and professional perceptions of the Built Environment. Showing the over-time vulnerabilities of planning through a systematic literature review should be considered a benchmark for the social satisfaction of spaces during the current pandemic. Compared to previous times, the lockdown restriction has revealed a different fulfilment as well as a different awareness of users. The pandemic has been, and still is, an incredible opportunity for us to pause for a moment to understand what is working and what is not in the choices Planning has adopted to date, testing the resilience of spaces for both living and working.

By revealing a high level of dissatisfaction exposed from the perspective of COVID-19, the change in the usage frequency of living places, such as the increased number of hours spent at home and the parallel reduction of hours spent in public and semi-public spaces, has contributed to a change in people's perception of spaces.

Thus, rather than focusing on future solutions, this study has aimed to collect the main issues and opportunities of planning. The critical aspects that emerged from the literature review during this pandemic are the importance of flexibility, proximity, green space and the correlation between mental/physical health and architecture. Proximity is an ongoing debatable aspect in architecture since it allows for determining a cohesive community while retaining social distancing. Over the recent years, we have witnessed the growth of cities with the expansion of suburbs lacking associated system services and mainly used as dormitories for the city. Today people are asking themselves if they could live in a specific space if faced with a lockdown again, and for this, they pay much more attention to their surroundings.

The same applies to green spaces and environments. Views over the green-blue spaces and easy access to them are in high demand. However, it is still challenging to incorporate them due to the existing social inequalities and the high price of what we consider today more than ever, the new gold: nature. Moreover, from design to urban planning, flexibility is another concept to consider, whatever the planning scale. As living beings, we are continuously evolving, and with us, nature is also in an ongoing process of change. We have learned that in a very short time, everything could change, and we probably need to address the term resilience not only as it applies to people and nature but also to the designing of the spaces that inevitably surround us and affect us.

Thus, what emerged even more strongly is the lack of a valuable transdisciplinary approach that could address people's needs to design the best places from a stylistic point of view and from the sociological, anthropological, psychological and health perspectives. These aspects were so far not considered to be significant, judging from the current opportunities in planning. For this reason, informative research about what high-quality space means in different fields should be more deeply analysed in order to refer to it as a regular informative method upon which planning should be based.

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TOWARDS A TECHNICAL SENTIMENT LEXICON FOR THE MAINTENANCE OF HUMAN-CENTRED BUILDINGS

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Abstract

Following the "Cognitive Building" concept, in a few years, building automation systems were drastically improved to collect a large amount of user data. However, despite this evolution and the research efforts in the field, human-building interaction remained one of the least mature fields of building science due to the occupants' complexity and diversity. Collecting data became simple and cheap, but transforming collected "data" into valuable "information" able to create an effective interaction between buildings and occupants remains complex.

This work contributes by proposing a method to translate unstructured data, coming from Computerized Maintenance Management System (CMMS), into information useful to improve the interactions between occupants and buildings in the management of the maintenance process. End-users' maintenance requests, collected through a CMMS, were used to create a technical sentiment lexicon able to predict the priority of an intervention based on an inverted naïve Bayes approach. Sentiment lexicons are part of sentiment analysis, an interesting research field introduced to study people's opinions, sentiments, emotions, and attitudes through Natural Language Processing (NLP). The technical lexicon is useful to immediately perform the priority assessment of contemporary end-users' maintenance requests, thus being more rapid than traditional Machine Learning methods.

Keywords

Human-building interaction, Maintenance, Computer maintenance management system, Text mining, Sentiment lexicon.

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1. INTRODUCTION

No more than ten years ago, the "cognitive building" concept was introduced, based on the idea that the rapid evolution of ICT and the availability of low-cost IoT devices would transform in a short time buildings from passive "containers" of occupants' activities to interactive environments. The concept evolved quickly, and the idea of the "digital twin" emerged to express the possibility of predicting the interaction between occupants and buildings in a digital replica of the real building. Following these concepts, and thanks to the large availability of low-cost sensors [1], building management activities were substantially improved during the last years [2], and CMMS (Computerized Maintenance Management System) was extensively introduced to manage building stocks.

CMMSs can collect end-user's maintenance requests, trace the management process, and collect information about the state of the systems and the occupants' perception. CMMSs can manage unstructured data [3, 4], typically e-mails written by non-technical end-users to give information about a specific issue. However, due to the use of the natural language and the characteristics of the occupants (e.g. level of experience with buildings, systems and components), this information is often imprecise and often mixed with personal perceptions about the system's state. Thus, the translation of the end-users' request into a work order (to solve the problem) by technicians is not a simple task, often requiring more time to manage the request than to solve the problem. Furthermore, the complexity of such a task increases depending on the number of daily contemporary requests, which can be particularly high in case of wide organizations hosted in large building stocks.

In other fields, text mining tools were introduced to solve this type of issue, thanks to their ability to discover hidden knowledge from massive and complex data stored in databases or other information repositories [5]. Text mining methods were used to translate occupants' feedback, comments and reviews on social and commercial platforms (data) into "information" useful to improve products and services [6].

Among the text mining methods, sentiment analysis (SA) recently received particular attention [7]. SA studies people's opinions, sentiments, emotions, and attitudes, often employed to extract opinion polarity and degree from different sources [8]. SA was also introduced in facility management to collect information about the status of building systems directly from end-users' perceptions [9] and to improve preventive maintenance strategies [10].

The most important indicators of sentiments are the "opinion" words [6], but also phrases and idioms can express sentiments [7]. A list of such words and phrases is called a sentiment "lexicon". Several general lexicons have been realized and are available, i.e. General inquirer lexicon, HU-LIU lexicon [6], MPQA subjectivity lexicon [11], SentiWordNet [12], and also emotion lexicons. Over the years, researchers have designed numerous algorithms to compile and improve such lexicons, considering that "opinion" words may have opposite orientations or polarities in different application domains or sentence contexts. Sentences without "opinion" words can even imply positive or negative sentiments or opinions of their authors, and many words or sentences may have opposite orientations or polarities in different application domains [7].

Sentiment analysis methodologies have been applied to analyze several aspects of the building management process [13] and to collect information about people's preferences and concerns about energy policies [14].

More recently, Natural Language Processing (NLP) models were also applied to the facility management of buildings, collecting sentiments and opinions from end-users [4], in order to improve the building operability and the cost of the management process [15]. Bortolini and Forcada developed a methodology, based on the TF analysis of words expressing the severity degree, to determine the typical problems that end-users complain about the building systems and their perceived severity [9]. Gunay et al. analyzed operators' work order descriptions in CMMS, extracting information about failure patterns in building systems and components [16]. The results provided insights into equipment breakdown of failure events, top system and component-level failure modes, and their occurrence frequencies. Bouabdallaoui et al. proposed a machine-learning algorithm based on NLP to manage day-to-day maintenance activities [17]. Sexton et al. compared NLP methodologies to extract keywords from maintenance Work orders [18]. Two emotion lexicon databases, the Ho-Liu database [6] and the NRC emotion lexicon, were used to extract data from semi-structured interviews and focus group discussions regarding housing management in India. Sentiment lexicons were convenient since they were much faster and less computationally intensive than Machine Learning (ML) methods. Indeed, just consider that the training and testing process of an ML method, such as an LSTM or BiLSTM RNN, normally used to manage this type of data, could require hours or days depending on the dimension of the dataset and the number of dedicated GPUs or CPUs.

Several general-purpose subjectivities, sentiment, and, also, emotion lexicons have been realized and are publicly available [6, 11, 12, 19, 20], but the accuracy of proposed methodologies and lexicons should be properly evaluated when applied to specific domains or to extract specific aspect-based sentiments.

Several studies have been performed to check the concordance of different lexicons in different domains [21]. Various combinations of existing lexicons and NLP tools have been evaluated against a human-annotated subsample, which serves as a gold standard. Cambria et al. described several comparative works based on human annotation approaches (Best-Worst, MaxDiff) [7].

However, despite a significant amount of research, challenging problems remain. A general, quick-to use and effective method for discovering and determining domain and context-dependent sentiments is still lacking [22].

D'Orazio et al. [23] demonstrated that SA is a powerful method to extract information from unstructured data but also that general and easy-to-apply word-based lexicons commonly used in other contexts cannot be simply applied to the field of building facility management because "technical" words are not recognized as "opinion" words in other fields. An example is represented by the words "falling" and "ceiling". These words express a serious problem for a technician when they jointly occur in a maintenance request, but this connection seems to be not properly recognized by lexicons, even if they are in the same polarized cluster [23]. Then it is necessary to develop technical lexicons to correctly apply these methods.

Given the above, this work proposes a method to translate unstructured data, coming from CMMS, into information useful to improve the interactions between occupants and buildings in the management of the maintenance process. End-users' (occupants') maintenance requests collected through CMMS are used to create a technical sentiment lexicon able to predict their priority, thus being sensitive to the application context of building maintenance. In particular, the method adopts an inverted naïve Bayes approach [24], which can be powerful by considering (1) the possibility of combining the priority impact of each "technical" word in the lexicon, as well as common words, and (2) the application quickness for the use of real-world data and in real-world conditions, also in respect to other common ML methods. This method, automatizing the priority assignment process, will reduce the time necessary to solve maintenance issues, improving the satisfaction level of the end-users about the functionality of the systems (HVAC, electricity, water, etc.), and thus also including impacts on building operation and comfort issues (e.g. indoor temperature, IAQ) as well as on the safety of the users (e.g. referring to safety systems, elevator, etc.).

2. METHODOLOGY

2.1. RESEARCH FRAMEWORK

A mathematical approach is proposed based on the Naïve Bayes theorem to develop the technical lexicon. In particular, the theorem has been inversely applied, deriving the polarity of technical words when used together from the priority scores assigned to a subset of a corpus of end-users' maintenance requests manually annotated by technicians with different expertise. The corpus comprises more than 12000 end-users maintenance requests. These requests were generated over 34 months by the personnel employed at Università Politecnica delle Marche (Ancona, Italy) and collected into the CMMS managed by the facility management general contractor (ANTAS spa). The Human Manual Annotation (HMA) process is based on a BWS (best-worst-scale) approach.

20 annotators, with three different expertise levels (high, mean, low), depending on their skills and work experience in the construction field, were presented with several 4-tuples of requests and asked to select the most positive one and the most negative one. 10 high-level, 4 mean-level, and 6 low-level annotators participated in the HMA task. A random subset of sentences has been extracted from the dataset, respecting the proportion of sentences by category type. 150 distinct 4-tuples were randomly generated through the "bwstuples" python script (http://valeriobasile.github.io/) so that each term was seen in five different 4-tuples. The score is given by the ratio between the number of times an item is chosen as "best /worst" and the number of times it appears [25]. The concordance level due to the different annotators has been checked through a correlation analysis based on the spearman method. To be robust with respect to possible outliers, the work of each annotator characterized by a rho-spearman correlation coefficient < 0.8 (for the mean value of the group of annotators) has been discarded, and the Krippendorfs' alpha coefficient was calculated. The K-alpha coefficient measures the concordance degree used in several fields.

The final score obtained for each of the 150 sentences, for the remaining annotators, is the mean of scores each annotator gives. The number of sentences used in the process has been chosen to grant that more than 90% of the words employed in the whole dataset are part of the subsample.

Thanks to the availability of annotated sentences, a mathematical reformulation of the naïve Bayes approach has been performed to extract the specific technical polarity content of each word. A method to calculate the technical-specific content has been proposed in Section 3 by assuming that: (1) the scores attributed by the technicians to each specific sentence are due to the words contained in the sentence, and that (2) the technical words are also opinion words.

Finally, the method has been applied to the extracted dataset to derive the proposed technical lexicon. R statistics (rel. 4.3) language has been used to perform the operations necessary to derive the lexicons by applying the mathematical formulation proposed in the following section.

2.2. THE NAÏVE BAYES APPROACH AND THE RELATED CRITERIA FOR EFFECTIVENESS ANALYSIS

Naïve Bayes is a well know ML classification method based on the Bayesian theorem. It has been extensively applied to classify data and text and predict a particular state of a system based on conditional probability calculation. In particular, from the number of times an event has occurred, the Naïve Bayes method derives the probability that it may again occur in future trials or observations [24]. The probabilities of the events are computed from their observed frequencies (a-posteriori probabilities).

In particular, Naïve Bayes theorem states that, given two events a and b:

$$P(a|b) = \frac{P(a|b) \cdot P(a)}{P(b)}, P(b) > 0 \; [1]$$

where:

$P(a|b)$ = conditional probability of observing an event a given that b is true

$P(b|a)$ = conditional probability of observing an event b given that a is true

$P(a)$ = unconditional *a priori* probability of a without any regard to b

$P(b)$ unconditional *a priori* probability of b without any regard to a

Knowing the unconditional probability of “a” and “b” (observed frequency) and the conditional probability of “b” given that “a” is true, it is possible to calculate the conditional probability of “a” given that “b” is true. To clarify the concept and show the application to the NLP, a simple example, adapted from [24], is explained considering a binary system (only two possible values for each sentence).

Suppose to have a dataset of 7 annotated sentences, regarding the internal climate, with an attributed polarity score: ⊕ (positive); ⊖ (negative).

1. it is nice climate ⊕
2. it is cold ⊖
3. it is not very cold ⊕
4. not nice ⊖
5. very cold ⊖
6. cold ⊖
7. very nice climate ⊕

By starting from the dataset, it is possible to calculate the frequencies of each word in each sentence and in the whole dataset:

w1 = it: 2 occurrences in ⊕, 1 occurrence in ⊖, in total 3;
w2 = is: 2 occurrences in ⊕, 1 occurrence in ⊖, in total 3;
w3 = nice: 2 occurrences in ⊕, 1 occurrence in ⊖, in total 3;
w4 = climate: 2 occurrences in ⊕, 0 occurrence in ⊖, in total 2;
w5 = cold: 1 occurrences in ⊕, 3 occurrences in ⊖, in total 4;
w6 = not: 1 occurrences in ⊕, 1 occurrence in ⊖, in total 2;
w7 = very: 2 occurrences in ⊕, 1 occurrence in ⊖, in total 3.

Through the calculation of the frequency, we can predict the probability P that a sentence containing the words (it, is, not, nice, cold) will be positively or negatively annotated, using the equations 2–7 obtaining PNB+, PNB-, and CNB, as described in the equations 8–11.

$$P_{NB+(it,\ is,\ not,\ nice,\ cold\ |\ \oplus)} = P(\oplus)\cdot(it\ |\ \oplus)\cdot(is\ |\ \oplus)\cdot(not\ |\oplus)\cdot(nice\ |\oplus)\cdot(cold\ |\oplus)\ [2]$$

$$P_{NB-(it,\ is,\ not,\ nice,\ cold\ |\ominus)} = P(\ominus)\cdot(it\ |\ \ominus)\cdot(is\ |\ \ominus)\cdot(not\ |\ominus)\cdot(nice\ |\ominus)\cdot(cold\ |\ominus)\ [3]$$

$$C_{NB} = \arg\max_{c_j \in C}(p_{NB+}, p_{NB-})\ [4]$$

where:

$$P(\oplus) = \frac{number\ of\ \oplus\ sentences}{number\ of\ total\ sentences} = \frac{S_{\oplus}}{S_T}\ [5]$$

$$P(\text{"}word\text{"}\ |\oplus) = \frac{frequency\ of\ the\ word\ into\ \oplus\ sentences}{frequency\ of\ the\ word\ in\ the\ corpus} = \frac{F_{(word\ \oplus\ sentences)}}{TF_{(word_{corpus})}}\ [6]$$

$$P(\text{"}word\text{"}\ |\ominus) = \frac{frequency\ of\ the\ word\ into\ \ominus\ sentences}{frequency\ of\ the\ word\ in\ the\ corpus} = \frac{F_{(word\ \ominus\ sentences)}}{TF_{(word_{corpus})}}\ [7]$$

$$P_{NB+} = 0.00001279\ (3/7\cdot 2/12\cdot 2/12\cdot 1/12\cdot 2/12\cdot 1/12)\ [8]$$

$$P_{NB-} = 0.00005228\ (4/7\cdot 1/8\cdot 1/8\cdot 1/8\cdot 1/8\cdot 3/8)\ [9]$$

$$C_{NB} = \arg\max_{c_j \in C}(P_{NB+}, P_{NB-})\ [10]$$

$$C_{NB} = \arg\max_{c_j \in C}(P_{NB+}, P_{NB-}) = \arg\max_{C_1=\oplus, C_2=\ominus} = (5.228\cdot 10-5; 1:27910-5) = \oplus\ [11]$$

The Naïve Bayes approach can also be used to predict the class of a specific sentence, for n-class systems, where n → number of annotated sentences, when each sentence has been "annotated" with a different specific value instead of a category.

3. THE INVERTED NAÏVE BAYES METHOD FOR END-USERS' MAINTENANCE REQUESTS ANALYSIS

The Naïve Bayes approach described in Section 2.2 can be inverted to obtain from an "annotated" dataset of sentences the contribution of each word contained in the sentence to the annotated score attributed to the sentence.

Starting from the assumption that each word comprised into a specific sentence can contribute to the score attributed to each sentence, it is possible to apply the method described in Section 2.2, inverting equations 6 and 7.

In particular, if we consider a dataset of sentences containing a set of words (A, B, … , N), equations 6 and 7 can be rewritten, for each sentence, to obtain equations 12 and 13:

$$\frac{S_{\oplus}}{S_T}\cdot\frac{F_{A_{\oplus sentence}}}{TF_{A_{corpus}}}\cdot\frac{F_{B_{\oplus sentence}}}{TF_{B_{corpus}}}\cdot\ldots\cdot\frac{F_{C_{\oplus sentence}}}{TF_{N_{corpus}}} = S_{\oplus} \rightarrow P(\oplus) = \frac{S_{(\oplus)}+S_{(\ominus)}}{S_{(\oplus)}}\ [12]$$

$$\frac{S_{\ominus}}{S_T}\cdot\frac{F_{A_{\ominus sentence}}}{TF_{A_{corpus}}}\cdot\frac{F_{B_{\ominus sentence}}}{TF_{B_{corpus}}}\cdot\ldots\cdot\frac{F_{A_{\ominus sentence}}}{TF_{N_{corpus}}} = S_{\ominus} \rightarrow P(\ominus) = \frac{S_{(\ominus)}+S_{(\oplus)}}{S_{(\ominus)}}\ [13]$$

where:

$F_{A,B,\ldots,N\oplus_{sentence}}$ = "A", "B", ⋯ , "N" *word frequency in the* ⊕ *sentence*

$F_{A,B,\ldots,N\ominus_{sentence}}$ = "A", "B", ⋯ , "N" *word frequency in the* ⊖ *sentence*

$TF_{A,B,\cdots,N_{corpus}}$ = "A", "B", ⋯ , "N" *word frequency in the corpus*

$S_{(\oplus\ or\ \ominus)}$ = *number of positive or negative sentences*

S_T = *total number of sentences*

$P\oplus, P\ominus$ = *positive, negative class probability*

Having a corpus where each sentence is annotated with a specific score, we can simplify equations 12 and 13, assuming equation 14. Then, joining equations 12 and 13, we can obtain a set of linear equations (equation 15).

$$S_{\oplus} = S_{(\ominus)} = 1 \quad [14]$$

$$\begin{aligned}
&\frac{1}{S_T} \cdot \frac{X_{1,1} \cdot F_{A_{sentence}}}{TF_{A_{corpus}}} \cdot \frac{X_{1,2} \cdot F_{B_{sentence}}}{TF_{B_{corpus}}}, \ldots, \frac{X_{1,N} \cdot F_{N_{sentence}}}{TF_{N_{corpus}}} = Score_1 \\
&\frac{1}{S_T} \cdot \frac{X_{2,1} \cdot F_{A_{sentence}}}{TF_{A_{corpus}}} \cdot \frac{X_{2,2} \cdot F_{B_{sentence}}}{TF_{B_{corpus}}}, \ldots, \frac{X_{2,N} \cdot F_{N_{sentence}}}{TF_{N_{corpus}}} = Score_2 \qquad [15] \\
&\ldots \\
&\frac{1}{S_T} \cdot \frac{X_{N,1} \cdot F_{A_{sentence}}}{TF_{A_{corpus}}} \cdot \frac{X_{N,2} \cdot F_{B_{sentence}}}{TF_{B_{corpus}}}, \ldots, \frac{X_{N,N} \cdot F_{N_{sentence}}}{TF_{N_{corpus}}} = Score_N
\end{aligned}$$

X1, 1, …., N, N are the unknown coefficients expressing, for each sentence, the contribution of each word to the score attributed to the sentence. If we now define $K_{N1,2,\ldots N}$ and $Z_{N1,2,\ldots N}$ (equations 16 and 17), the whole set of linear equations appears in the following form (equations 18):

$$K_{N_{1,2,\ldots,N}} = S_T \cdot TF_{A_{corpus}} \cdot TF_{B_{corpus}} \cdot \ldots \cdot TF_{N_{corpus}} \quad [16]$$

$$Z_{N_{1,2,\ldots,N}} = F_{A_{sentence}} \cdot F_{B_{sentence}} \cdot \ldots \cdot F_{N_{sentence}} \quad [17]$$

$$\begin{aligned}
&\frac{K_{N_1}}{Z_{N_1}} \cdot (X_{1,1} \cdot X_{1,2}, \ldots, \cdot N_{1,N}) = Score_1 \\
&\frac{K_{N_2}}{Z_{N_2}} \cdot (X_{2,1} \cdot X_{2,2}, \ldots, \cdot N_{2,N}) = Score_2 \qquad [18] \\
&\ldots \\
&\frac{K_{N_1}}{Z_{N_1}} \cdot (X_{N,1} \cdot X_{N,2}, \ldots, \cdot N_{N,N}) = Score_N
\end{aligned}$$

It is not possible to directly solve the linear equation set because of the impossibility of finding two sentences composed of the same words, but it is possible to find an approximate solution. Assuming that the contribution of each word to the score of each specific sentence is equal (equations 19), we can write, for sentence 1, equations 20 and 21. Repeating the same process for each annotated sentence, we can obtain a vector Q expressing the contribution of each word contained in each specific sentence to the total score attributed to the sentence (equation 22):

$$X_{1,1} = X_{1,2} = \cdots = X_{1,N} = Q_1 \ , \ W_1 = words\ in\ the\ sentence\ 1 \quad [19]$$

$$\frac{K_{1_1}}{Z_{1_1}} \cdot Q_1^{W_1} = Score_1 \quad [20]$$

$$Q_1 = \sqrt[W_1]{Score_1 \cdot \frac{Z_{1_1}}{K_{1_1}}} \quad [21]$$

$$Q = \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_n \end{bmatrix} \qquad [22]$$

$$Q_1 = polarity_1 \cdot \sqrt[W_1]{SCORE_1 \cdot \frac{Z_{1_1}}{K_{1_1}}} \quad [23]$$

$$\frac{\sum_1^N Q_{obtained\ by\ the\ word}}{sentences\ containing\ the\ word} \quad [24]$$

Considering that the BWS process, used to annotate the sentences, produces scores ranging from -1 to 1, it is necessary to correct the Q equation extracting the polarity (the sign of the score) to avoid errors as described by the equation 23, where $polarity_1$ = -1 or 1 (depending on the polarity of sentence 1).

Considering that for the same word we will obtain different Q, for each sentence we will obtain the approximate solution of the unknown coefficients (equation 18), summing Q values obtained for each word and each sentence and dividing the obtained value by the number of sentences comprising the word (equation 24). The approximate solution can be furtherly refined with an iterative process until convergence.

4. THE MANUAL ANNOTATION PROCESS ON THE CASE STUDY

In order to apply the proposed method, a manual annotation process based on the BWS (best-worst-scale) approach has been performed to attribute a score to each sentence within a sample of 150 end-users' maintenance requests. Twenty annotators attributed a priority score to the sentences through the BWS approach. The score ranges from -1 to 1 and represents the intervention priority to assign to each end-users' request with respect to the other maintenance requests.

A correlation analysis (Fig. 1), based on the spearman method (due to the non-normality of the sample), has been performed to check the concordance between the annotators. For the same sentences, the scores attributed by different annotators concerning each other and the mean value were correlated. Observing the values of the last column (Spearmans' Rho coefficient for each annotator concerning the mean value), three annotators appear strongly diverging from the others (two negative correlations and one not-valuable result). The other annotators attributed similar scores with correlation coefficients in the range of 0.71–0.9. In order to reduce discordances and obtain a unique score for each sentence, the whole work of the annotators diverging from the mean of the group (rho < 0.8) was discarded. The final Krippendorfs' alpha coefficient was then calculated, obtaining a value = 0.714 (> 0.67), thus expressing an adequate concordance level.

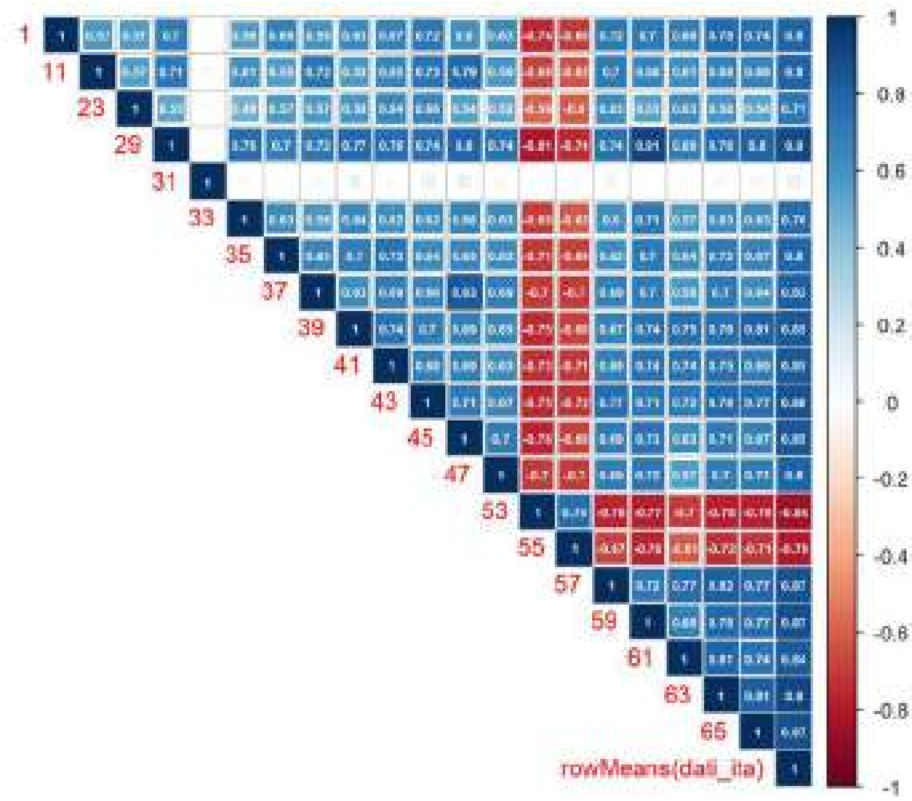

Fig. 1. *Correlogram based on the Spearman method. Colour represents a positive or a negative correlation. White numbers inside the boxes represent Spearmans' Rho coefficients. Red numbers represent the code of each annotator. The last column, named rowMeans(dati_ITA), shows the correlation coefficients of each annotator with the mean value of the group of annotators.*

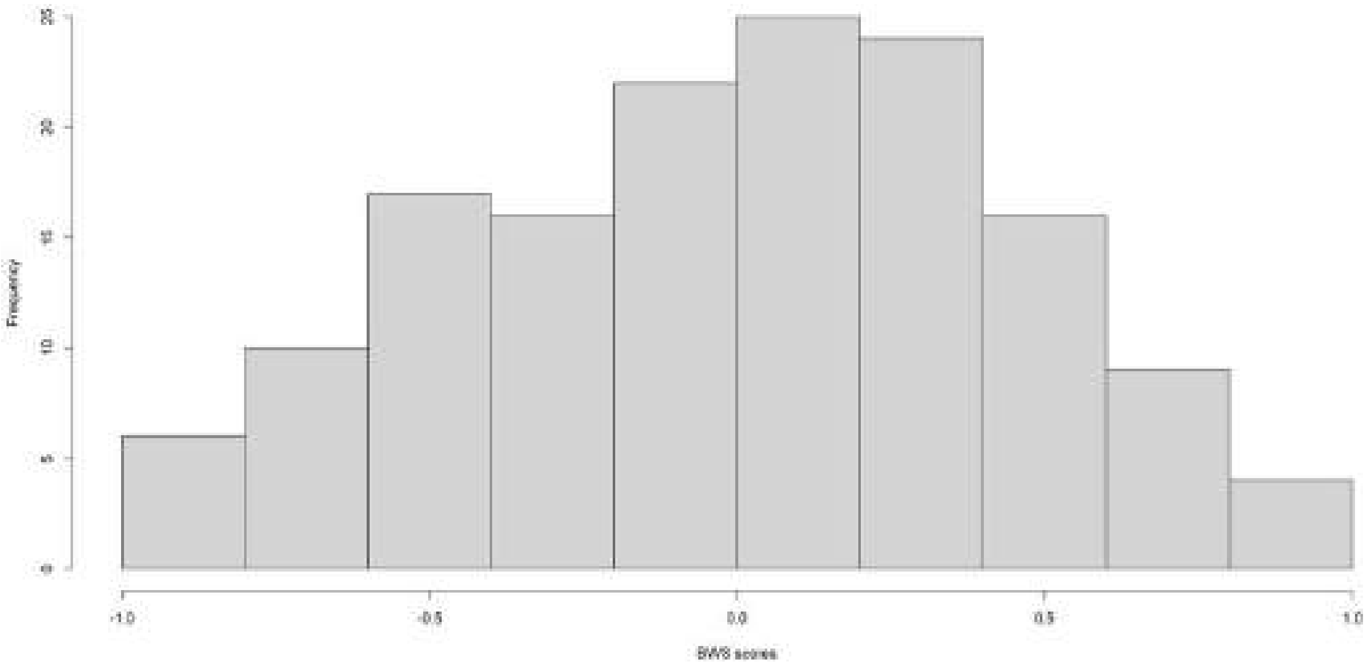

Fig. 2. *Distribution of the BWS scores obtained through the HMA.*

Then, the mean of the scores attributed by the remaining annotators was calculated for each sentence. Finally, the 150 sentences were ordered on a scale of -1 (high priority) and 1 (low priority).

Figure 2 shows the distribution of the scores obtained through the manual annotation process based on the BWS approach. As expected, the scores are normally distributed.

5. APPLICATION OF THE PROPOSED METHOD TO THE CASE STUDY

To show the application of the proposed method, an R script has been written, and the Q values were calculated for the words contained in a limited set of sentences, starting from the dataset of sentences previously analyzed and applying the equations described in the previous Section 3. Four sentences of the dataset were adapted to have a limited set of words to calculate frequencies and Q values. Table 1 shows the sample sentence set and the scores attributed to each sentence. After a preliminary remotion of the stopwords (common words not expressing specific opinions), symbols and punctuations, performed using the TM package, the phrases were reduced to a limited set of words repeated in the sentences.

Code	Original sentences	Reduced sentences	Score
1	The tap leaks water	tap leaks water	-0.4
2	The tap leaks a lot of water	tap leaks lot water	-0.6
3	The tap leaks a river of water	tap leaks river water	-1
4	The tap leaks a little amout of water	tap little leaks little amount water	-0.1

Tab. 1. *Original and reduced sentences, with the attributed scores. Reduced sentences were obtained with a stopword remotion process.*

Then the DTM (document term matrix) was built. A DTM is a matrix expressing each word's presence or absence in each sentence (Tab. 2).

Sentence/ Word	tap	leaks	water	little	lot	river	amount
1	1	1	1	0	0	0	0
2	1	1	1	0	1	0	0
3	1	1	1	0	0	1	0
4	1	1	1	1	0	0	1
Frequency	4	4	4	1	1	1	1
Q	-0.1985	-0.1985	-0.1985	-0.0520	-0.0550	-0.0625	-0.0520

Tab. 2. *Document term matrix.*

Finally, equations 20–24 were applied, obtaining frequencies and Q values for each of the words comprised in the dataset. The little differences that we found between "little", "lot", and "river" can be explained by the very limited dimension of the sample chosen to show the application of the proposed method. Only with a very large number of sentences is it possible to calculate frequencies, not depending on the specific dataset, and to reach enough accuracy to realize a general technical lexicon.

6. CONCLUSION

This work proposes a method to use polarity scores attributed to a set of annotated end-user maintenance requests to extract the "specific polarity content" of each word contained in the dataset. The technical lexicon is useful to quickly predict the priority to assign to contemporary end-users' maintenance requests with respect to traditional ML methods.

The work is based on the end-users' maintenance requests collected into a CMMS by a general facility manager contractor. From a dataset containing more than 12000 end-users' maintenance requests, 150 sentences were extracted, and a BWS manual annotation approach was applied. The manual annotation was performed by 20 annotators obtaining priority scores for each sentence ranging from -1 (high priority) to 1 (low priority). Then a mathematical reformulation of the naïve Bayes classification approach has been proposed to extract from the annotated sentences the priority expressed by each word. Concerning the other common ML methods, the proposed approach, based on SA methods, can give affordable results with very limited use of computational resources.

The proposed approach has been applied to a limited sample dataset to show the validity of the approach. Following the proposed method, future works will transform data collected through CMMSs to create a complete technical sentiment lexicon able to predict the priority sentiment expressed by occupants through unstructured end-users' maintenance requests. This effort will ensure applying the lexicon and the proposed methodology to building maintenance and management tasks in complex built environments.

The real-world application could take benefit from the outcomes of this work. Relational databases used in commercial CMMs could be easily integrated with the proposed methodology, and thus the textual data collected (end-users requests) could be simply pre-processed to calculate the priority score thanks to the proposed technical sentiment lexicon. Then, collected data can be then screened by technicians once the automatic assignment process has been performed, by then (1) supporting the quick identification of the most urgent needs that can cause interruptions of services for users, as well as safety and discomfort issues, and (2) allowing technicians to focus on the next management tasks. Such a kind of aid could be fundamental, especially for facility management in large and complex organizations. Technicians could then focus on the deployment of corrective actions, e.g. by detecting and assigning which staff members' expertise is needed to solve the fault. In this sense, future works could also employ ML methods to support other maintenance tasks, e.g. work category assignment, thus further reducing manual effort by technicians and boosting fault solutions.

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FOSTERING THE CONSENSUS: A BERT-BASED MULTI-LABEL TEXT CLASSIFIER TO SUPPORT AGREEMENT IN PUBLIC DESIGN CALL FOR TENDERS

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Abstract

Natural Language Processing (NLP) is a branch of Artificial Intelligence (AI) concerned with allowing computers to process natural human language. NLP is applied to solve several tasks in the design and construction process. However, in scientific literature, no applications are related to the pre-design phase and the processing of quality objectives and needs. The pre-design phase aims to reach a consensus between the stakeholders' quality demands and the design solution, relying on written natural language. Human language is the most pervasive and richest form of human knowledge representation and communication; however, at the same time, it is ambiguous, prone to misinterpretations, and hardly machine computable. Moreover, the mandatory procedural steps of the public tender procedure exacerbate the risk of misinterpretations inherent in using natural language. The study provides a methodology to design, assess, and evaluate an NLP tool based on the latest language model (i.e., BERT) to translate quality demands sentences into an evaluation grid in the Italian public tender context. The methodology is validated against a case study of an educational facility tender. The first results show good accuracy and capability of the NLP system to translate natural language into a numerical grid to support communication and foster consensus among actors, clarifying the appointing party and end-users' objectives to be reached via the design proposals.

Keywords

Deep Learning, Natural Language Processing, Knowledge mirroring, Knowledge representation, Educational facilities tender.

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1. INTRODUCTION

1.1. TEXT SOURCES AND NATURAL LANGUAGE PROCESSING (NLP) IN THE CONSTRUCTION SECTOR

The combination of the latest technological advances and the increasing number of different typologies of available data sources has fostered data-driven research in the construction industry. The design and construction process deals with different and complex forms of information that are mainly captured and exchanged using text documentation: in the construction sector, «documents are interfaces, used to access and navigate through collections of information» [2]. Among the recent technologies, various text-based knowledge discovery techniques (i.e., Text Mining, Text processing, and Natural Language Processing) have emerged as a rapidly growing set of literature, aiming at processing text data and information as one of the leading sources of analysis [1]. In particular, existing studies assessed and applied Natural Language Processing (NLP) technology to process different document types in the construction sector [8], such as contracts and legal agreements [3], design requirements specification [4], risk and safety reports [5, 6], building legislation [7].

NLP refers to the branch of Artificial Intelligence (AI) concerned with giving computers the ability to process natural human language in written or verbal form. Project, Safety, and Risk Management are the areas with the highest number of applications. Moreover, cases of combined applications of the Building Information Modelling (BIM) method and text processing to streamline Automated Compliance Checking tasks are currently being investigated, and NLP-based systems to convert regulatory information represent an active field of research [9]. However, in the scientific literature, no applications are related to the pre-design phase and specifically to the processing of quality objectives and needs expressed in written form via text documents [10]. The pre-design phase's main objective is to foster a consensus between the stakeholders' and end-users' quality demands and the design solution. The definition and sharing of quality demands primarily rely on natural language, which is the most pervasive and valuable form of human knowledge. However, natural language is subject to ambiguity and misinterpretation and is hardly machine-processable [11].

NLP technology can still be considered an innovative topic, especially for NLP applications in the design and construction research field. Consequently, the following section proposes an overview of the latest developments in NLP algorithms in the computer science research field.

1.2. NLP LATEST DEVELOPMENTS

Recently, NLP research has significantly improved with novel approaches that emphasize semantic meaning and context awareness, using the generalization capability of modern Deep Learning (DL) algorithms that enable semantic meaning processing and streamline NLP tasks.

Leading global companies such as Google and Facebook have helped popularize the use of pre-trained language models for word embedding (i.e., the conversion of text into numbers). In fact, for computers to comprehend human language, text must be converted into numbers (i.e., matrixes and vectors). The first pre-trained word embedding models, such as Word2vec, released by the Google team in 2013 [12], and Glove, published by the Stanford NLP research [13], are defined as non-contextual models. These models could not differentiate the different meanings of a word according to the context, failing to capture the impact of surrounding words on the meaning of individual words.

The limitations of non-contextual models prompted the development of language models able to provide contextualized embedding. The first example is ELMo (Embeddings from Language Models), which provides a deeply contextualized word representation that directly addresses the challenges of modeling complex characteristics of word use and how words use varies according to the context (i.e., polysemy phenomenon) [14]. The latest example is BERT (Bidirectional Encoder Representation from Transformers), released by the Google research team, which overcomes the main limitation of previous standard language models, which are unidirectional and limit the choice of architectures that can be used during the pre-training phase [15]. Both ELMo and BERT-based models can learn contextual relationships between words in a text by emphasizing semantic meaning and the impact of the context and, as a result, they are defined as context-aware models. A further key contribution of Google's BERT was the use of the pre-training using unlabeled text by conditioning jointly on both left and right context in all layers and the possibility to fine-tune the model [15, 16]. In fact, the BERT model is pre-trained on a massive amount of text data in an unsupervised manner to learn general linguistic patterns. The BERT model can be easily fine-tuned by adding a single output layer to create state-of-the-art models for a wide range of NLP applications on specific knowledge domains without an excessive array of new data [15]. From this point of view, BERT can be defined as a basic framework and a starting point for producing BERT-like versions fine-tuned on specific knowledge domains.

1.3. NLP APPLICATION IN ITALIAN PUBLIC DESIGN CALL FOR TENDERS

Considering the Italian public design call for tenders procedure, three main actors are involved: the appointing party, the design teams competing for the tender, and an external commission in charge of evaluating the design proposals. Each actor in the tender procedure has well-defined goals and roles:

1. the appointing party defines needs, objectives, and requirements, representing the end-users' needs to be satisfied through the design project. The Italian regulation requires the appointing party to communicate the needs in text form via a design guidance document called *Documento di Indirizzo alla Progettazione* (DIP);
2. the design teams participating in the call for tenders aim to deliver a design proposal to satisfy the appointing party and end-users' demands and win the call for tenders;
3. the external committee, composed of experts appointed by the appointing party, evaluates the various design proposals to identify the best design project, i.e., the most compliant with the DIP.

The DIP represents the appointing party and end-users' expectations about the design and, ultimately, about the building in a text form. The DIP structure is regulated by national law, and it has different mandatory contents which can be grouped into two main sections. A quantitative section provides technical requirements (e.g., minimum square meters per student (m^2/student)), economic and legal constraints (e.g., construction cost (€/m^2)), and regulations (e.g., minimum dimensions required by regulations: minimum height) that can be defined through alphanumeric parameters. A qualitative section describes quality objectives, needs, and demands defined and shared through verbal and natural language expressions (e.g., space flexibility or spatial and volumetric integration within the context).

During the design call for tenders procedure, the different actors are prohibited from communicating with each other. Moreover, each design team and the external committee must refer to the DIP to understand the main appointing party objectives during the design proposals' definition and evaluation, respectively. Consequently, a hierarchical organization of the appointing party's objectives and needs is typically manually implemented based on the actors' education, knowledge background, and experience and, accordingly, can be strongly subjective. This can lead to different interpretations of the relative importance of each quality objective due to the subjectivity of the DIP interpretation caused by the impossibility of confrontation and the absence of consensus among the involved actors. This, in turn, can ultimately cause a quality gap between the DIP quality objectives and needs and the design proposals. In fact, design proposals are typically defined and evaluated relying on the subjective view of individuals, thus increasing the risk of misinterpretations inherent in the use of natural language.

In such a context, the study proposes a methodology to design, assess, and evaluate an NLP tool based on the latest language model (i.e., Google BERT) to translate quality demands sentences included in a DIP into numerical values to support the definition of an evaluation grid, aiming at:

- reducing misinterpretation, or at least minimizing the different interpretations, of the relative hierarchy of quality objectives expressed by the appointing party, by defining a common and shared evaluation system;
- supporting the design teams to clearly identify the relative importance of the quality objectives and demands to be pursued by the design proposals;
- supporting the external committee in evaluating the design proposals according to the importance of the quality objectives and demands expressed in the DIP.

Summarizing, the evaluation system set by processing the DIP qualitative section via the proposed NLP tool aims to create a consensus about the relative hierarchy of quality needs and objectives among the three main actors involved. Consequently, the possible interpretations of the hierarchy and weights of the appointing party objectives by the design teams and the external committee are minimized by providing them with an evaluation grid of the hierarchized objectives resulting from applying the NLP tool to the DIP quality objectives section. A case study is selected to assess the proposed methodology on a real DIP document for designing and constructing an educational facility.

2. METHODOLOGY

In order to develop an NLP-based tool to process and translate the quality objectives expressed in a DIP into an evaluation grid, which must represent the computational counterpart of the natural language information, the automatic labeling task was identified as the most suitable to achieve the goal.

Among the NLP techniques, the Multi-label Text Classification (MTC) was selected, which is a text analysis technique that automatically applies one or more predefined classification labels to a single text or sentence. Unlike common classification tasks, in which class labels are mutually exclusive, multi-label classification allows predicting and assigning multiple mutually non-exclusive classes, i.e., the predefined labels.

As stated, the research study aims to develop an NLP-based system to perform a multi-label classification to automatically process and translate the needs expressed in a DIP document into an evaluation grid. The predefined labels for the MTC are the general objectives guiding the design processes and evaluating design proposals. The MTC is performed to automatically assign labels, i.e., the predefined objectives, to each DIP sentence, also assigning a weight to each label depending on the correlation of the sentence with each objective/label. Once applied the NLP tool to all DIP quality section sentences, a priority ranking of the DIP quality objectives is generated according to their total weights. Consequently, an evaluation grid is defined, which can eventually be revised by the appointing party and then shared with design teams and the evaluation committee to achieve a convergence of consensus among the three main actors (Fig. 1).

2.1. NLP TOOL DEVELOPMENT AND EVALUATION

As stated, the NLP tool is trained to classify sentences by assigning multiple labels, taken from a predefined list, to the natural language expressions. The main activities to develop the tool, explained in detail in the following paragraphs, are listed as follows: labels definition, training and validation dataset production, model fine-tuning, and performance evaluation.

2.1.1. LABELS DEFINITION

The NLP tool must be trained to classify sentences according to a set of predefined labels. To create a consensus on labels, which represent the interests and quality objectives of appointing parties and end-users, the set of labels must be jointly defined by them, when possible, and by domain experts (architects, building engineers, and designers).

2.1.2. TRAINING AND VALIDATION DATASETS DEFINITION

The proposed NLP tool is based on the BERT language model, which is based on a neural network architecture optimized for language processing. The pre-trained BERT language model must be fine-tuned to solve the

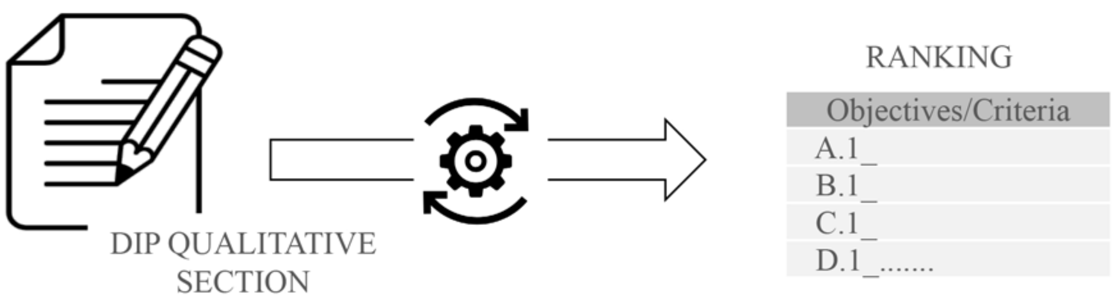

Fig. 1. *Schema of the proposed methodology.*

multi-label classification problem in the architecture and design knowledge domain. Consequently, a certain amount of training and validation data is needed. In particular, two datasets are defined:

- a training dataset for the first fine-tuning activity, which is used to further train the BERT model: the model learns from this dataset;
- a validation dataset to evaluate the performances of the trained model: the validation dataset is the set of data used to provide an unbiased evaluation of the model.

The general dataset is defined and then randomly split into the training and validation datasets at a 0.8:0.2 ratio.

The general dataset is defined by selecting DIP sentences and manually assigning labels, which is a critical task influencing the tool's accuracy and capability to automatically process and properly label the needs and quality objectives.

The production of the general dataset must result from a collaboration among experts with knowledge in the architectural, design, and construction fields. In addition, experts of specific knowledge domains, according to the specificity of each practical application of the methodology, must be involved in producing the general dataset. The involvement of domain experts allows for a proper representation of the knowledge domain and the avoidance of bias in the production of the general dataset. Consequently, the pre-trained BERT language model can be properly fine-tuned, representing a less biased capability of the group of experts to represent the knowledge domain.

Moreover, to further avoid any bias in the production of the dataset, each expert must be asked to independently propose a hypothesis for labeling each sentence. Then the experts would share their hypothesis and, in case of disagreement on some labels, they would be asked to share the motivation for their label choices and converge on a single common proposal. In fact, the construction of the dataset by different experts allows the model to represent and use their collective knowledge in the labeling activity.

By representing a collective intelligence of a group of people, larger than the ability of a single expert to judge and classify quality objectives related sentences, the NLP system aims to avoid subjectivity in interpreting textual information. Furthermore, the NLP tool will likely outperform the capability of a single expert to manage the complexity of analyzing several sentences, representing the group of experts' knowledge.

2.1.3. MODEL FINE-TUNING PARAMETERS

Once defined the dataset to properly train the BERT model, a set of hyperparameters must be defined. A hyperparameter is a variable configuration external to the model whose value cannot be estimated from the data. The list of hyperparameters used for the BERT NLP tool training follows:

- MAX_LEN: maximum number of tokens (words) processed during the training;
- TRAIN_BATCH_SIZE: refers to the number of training examples used in one iteration. A batch size of 32 means that 32 samples from the training dataset will be used to estimate the error gradient before the model weights are updated;
- VALID_BATCH_SIZE: refers to the number of examples used to validate in one iteration. A batch size of 16 means that 16 samples from the validation dataset will be used to validate the model;
- EPOCHS: an epoch is an entire transit of the training data through the algorithm. At each epoch, the internal model parameters of the dataset are updated. A training epoch ends when the learning algorithm has made one pass through the subgroups of the training dataset. The dimension of the subgroups is defined by the training batch size;
- LEARNING_RATE: it defines the adjustment in the neural network weights with respect to the loss gradient descent, determining how fast or slow the model will move towards the optimal weights.

2.1.4. PERFORMANCE EVALUATION METRICS

In order to measure the system's accuracy, the model predictions are compared with the human annotation, considered the best standard, and the F1-score metric is selected to measure the accuracy [17]. An explanation of the metrics utilized for the evaluation of the model is provided as follows:

- False Positives (FP) occur when a classifier predicts a label that does not match the input sentence. Considering the sentence “Spaces must be accessible”, if the model assigns the labels “Space flexibility” and “Space maintainability”, both errors are false positives;
- False Negatives (FN) occur when a classifier misses a label that matches the input sentence.

Considering the previous example, if the classifier does not predict “Space accessibility”, this is an example of a false negative.

Similarly, there are two ways classifier predictions can be corrected: True Positives (TP) and True Negatives (TN), described as follows:

- True Positives occur when a classifier correctly predicts the existence of a label;
- True Negatives occur when a classifier correctly predicts the in-existence of a label.

All the combinations are shown in Table 1.

		Predicted label	
Actual label		Positive (Pp)	Negative (Np)
	Positive (P)	True Positive (TP)	False Negative (FN)
	Negative (N)	False Positive (FP)	True Negative (TN)

Tab. 1. *Possible combination of True/False positives and True/False negatives.*

Consequently, performance metrics can be calculated, i.e., Precision, Recall, and F1-score [18]:

- Precision is the ratio of correct predictions among all predictions of a certain class, i.e., the proportion of True Positives among all positive predictions (1);
- Recall is the ratio of examples of a certain class that the model has predicted as belonging to that class, i.e., the proportion of True Positives among all true examples (2);
- F1-score is the harmonic mean of a certain class Precision and Recall; it can be considered as an overall measure of the quality of the classifier predictions (3).

$$Precision\ (P) = {TP}/_{FP + TP} \quad (1)$$

$$Recall\ (R) = {TP}/_{FN + TP} \quad (2)$$

$$F_1 = {2PR}/_{(P + R)} \quad (3)$$

F1-score values can range from 0 to 1. F1-score values equal to 1 represent a model that perfectly matches each observation with the correct label, and F1-score values equal to 0 represent a random classifier, i.e., a model that cannot match any observation with the corresponding label. Consequently, to evaluate the model performances, for each label, the authors agreed on a threshold value of the F1-score equal to 0.5, which is used to evaluate the tool predictions.

2.1.5. NLP TOOL OUTPUTS

Once the model is fine-tuned and the tool performances are evaluated, the NLP tool can be used to process new sentences and assign the corresponding labels (e.g., O.1. Spatial flexibility) and the accuracy degree with which the labels are associated to the new sentences (Fig. 2). The accuracy degree values of each processed sentence represent the weights of the labels and thus the relative priority of the labels/quality objectives for the single sentence.

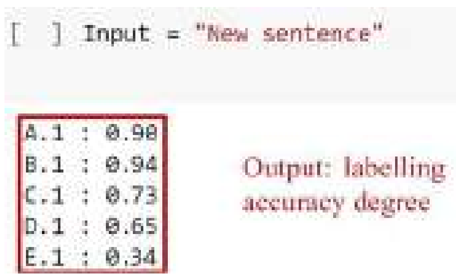

Fig. 2. *NLP tool outputs format.*

The accuracy values/weights of the labels obtained by processing all the sentences can then be summed and normalized to define the total weight of each label for the entire DIP (4).

$$Label\ Weight_i = \Sigma\ (L_i) \Big/ \Sigma\ (L_1) + \Sigma\ (L_2) + \Sigma\ (L_3) + \cdots + \Sigma\ (L_n) \quad (4)$$

where Li denotes the confidence of the i-th label, $i = (A.1, B.1, C.1..., P.1)$

The total weights of the labels represent the relative importance of the quality objectives to be pursued by the design teams in the definition of the design proposals and, at the same time, the evaluation criteria to be used by the external committee in the evaluation of the design proposals. The use by the design teams and the external committee of the same set of objectives, prioritized according to the appointing party's needs as expressed in the DIP, allows for an increase in the consensus among the three main actors about the most important objectives for the specific design.

3. CASE STUDY

3.1. CASE STUDY: *PROGETTO ISCOL@*

As introduced in Section 1, the case study aims to apply and assess the proposed methodology on a DIP document to design and construct a new school building. Since a school project has a high heterogeneity of quality objectives, needs, and requirements, and a high impact on the social and urban context, it was considered an appropriate building typology to assess the methodology. Specifically, the NLP tool is assessed on an Italian regional project, *Progetto Iscol@*, started in 2014 to realize several new school buildings in Sardinia. The Sardinian Regional Council introduced the *Progetto Iscol@* to address the problem of the backwardness of the regional educational system. The *Iscol@* team aims to renovate and expand the regional school building stock, improving the educational offer. The public investment of 265 million euros also has the economic objective of reactivating the Sardinian construction industry, setting a school system focused on architectural quality and social and environmental sustainability of the interventions.

At the beginning of *Progetto Iscol@*, the Sardinia Region shared general indications and guidelines for the drafting and the main contents of the DIPs to be produced by the involved local municipalities. Using common guidelines ensures that all DIPs follow the regional strategies, homogenizing the objectives of the interventions on the building school regional portfolio. In addition, a standardized evaluation grid for the design proposals evaluation process was established by the *Iscol@* team and shared with the local municipalities.

After completing the first set of calls for tenders and school designs of *Progetto Iscol@* in 2021, it was possible to analyze the impact of using a standardized evaluation grid (with fixed priority and weights of the predefined objectives) for all projects. On one hand, it was a useful tool to define and keep the focus on shared criteria and objectives that are in line with *Iscol@* strategic goals. On the other hand, a standardized evaluation grid with fixed priority and weights of the objectives is an overly rigid method to evaluate projects located in different contexts and with divergent specificities. In fact, there is an inner specificity of design and construction projects: buildings are considered "prototypes of themselves" and are strictly correlated and influenced by the context and the specific socio-economical and territorial needs. The use of fixed objectives priority and weights ultimately tends to flatten results, preventing a focus on the specificity and needs of each project.

Customizing the order priority and weight of the objectives for each call for tender, which is the output of the proposed NLP tool, can introduce the proper flexibility and specificity in the procedures.

Two phases of the *Progetto Iscol@* have been performed as of now: the first phase included ten project design competitions, and the second phase fifteen calls for tenders. All ten DIPs from the first phase and ten DIPs from the second phase were collected and used to produce the dataset (training and validation datasets), while the remaining five DIPs of the second phase were used to test the fine-tuned NLP system.

3.2. TOOL DEVELOPMENT AND EVALUATION

In this sub-section, the NLP tool fine-tuning is presented. The tool is trained and evaluated through the following steps described in the methodology section.

3.2.1. LABELS LIST

A list of predefined labels, defined within *Progetto Iscol@*, was already available for the proposed case study. The labels result from cooperation among experts and end-users (i.e., architects, designers, pedagogues, agronomists, and citizens). The list of predefined labels/ objectives and the number of related sentences for the definition of the dataset (training and validation datasets) is provided in Table 2.

Labels/Objectives list	Number of Sentences
A Sociocultural value:	
A.1 Capability of the school building to be used as a Civic Center	130
B Creation of ecological awareness in users	
B.1 Visibility and integration of sustainable design choices (educational medium) and integration of the intervention into nature and application of landscape enhancement strategies	42
C Development of a sense of belonging and respect for the common thing:	
C.1 Possibility of personalization of spaces and equipment to prevent vandalism creating a feeling of belonging	24
D Architectural and landscape quality of the intervention and integration with the pre-existing context:	
D.1 Spatial and volumetric integration of the intervention in the context and with existing buildings (shape, materials, colors, connections etc.) and proper mediation with the demand for visibility and architectural quality of the intervention as a building containing public functions	128
E Quality of layout plan:	
E.1 Articulation of spaces and accesses with a focus on simple and clear identification of the various functions, including using colors and signages	63
E.2 Presence of green spaces as an integral part of the design	32
F Indoor space quality:	
F.1 Perceptual quality (natural and artificial light) and psychophysical comfort (visual, thermo-hygrometric, acoustic etc.) to promote comfort and learning	128
F.2 Indoor air quality and healthiness	26
G Durability and maintainability:	
G.1 Cleanability, durability, maintainability, and replaceability of landscaping, materials, and greenery to reduce operating and maintenance costs	46
I Accessibility to the area:	
I.1 Integration of the intervention with the road system and distinction between driveways and bicycle and pedestrian paths; provision of areas and equipment to encourage slow and non-motorized mobility	36
I.2 Ensuring accessibility and usability for people with disabilities	45
L Integration between architecture and innovative pedagogical method:	
L.1 Fostering interactions between students and teachers, group work and peer learning (collaborative learning and peer tutoring) by supporting innovative and inclusive teaching. Architecture should support the idea of space as a third teacher	201
L.2 Visual and spatial continuity between outdoor (green and non-green) and indoor environments to encourage outdoor educational activities and enhance contact with the natural environment (outdoor space can be used as a second classroom). Connection between classroom and circulation spaces. The architecture should support the concept of openness of the traditional classroom and the concept of learning landscape	107
M Minimization of environmental impact with a view to ameliorative change:	
M.1 Use of renewable, natural (non-harmful), local materials or materials with recycled content	44
M.2 Minimization of the impact of the building on the surrounding environment (noise, light, water pollution, heat island effect, minimization of land consumption and use of soil defense strategies etc.)	90
M.3 Integration between design and renewable energy production systems and exploitation/management of solar, light, and natural cooling and heating inputs	48
M.4 Requests regarding energy standards and minimization of consumption (energy, water etc.) including using monitoring systems	102
N Safety:	
N.1 Ensuring safety during school activities and separation between activity conducted by people not belonging to the school staff, maintenance activities (spaces and paths), the adequate delimitation of the school perimeter, and need for control/supervision	34
O Flexibility and adaptability of spaces:	
O.1 Spatial flexibility (furniture, facilities etc.)	204
O.2 Temporal flexibility, possibility of use during curricular and extracurricular hours by citizens and long-term temporal flexibility, adaptability of spaces (readiness for change, adaptability)	118
P Fostering the use of multimedia technologies in education:	
P.1 Usability of technological devices and integration with learning theories. Integration of space and technology; widespread presence of ICT technologies	106

Tab. 2. *Labels list and description.*

3.2.2. TRAINING AND VALIDATION DATASETS DEFINITION

In order to fine-tune the model, the dataset was defined by manually identifying, collecting, and labeling the sentences from the qualitative sections of the DIPs, according to the procedure described in the methodology section. The production of the general dataset resulted from a collaboration between three experts with knowledge in the architectural, design, and construction fields. In addition, since the proposed NLP system is applied to a specific case study (*Progetto Iscol@*), a deep knowledge of the strategic objectives of *Progetto Iscol@* was needed to correctly label the training sentences. Since *Iscol@* members could not be directly involved in the project, a preliminary study of the overall goals, guidelines, and context of *Iscol@* was conducted by the three selected experts before labeling the training sentences.

In addition, the authors want to highlight that, as the labeling and dataset definition is a group activity, the dataset should represent the collective ability and sensitivity of the group of people and experts. The dataset and, consequently, the NLP tool should be less biased and with a lower grade of subjectivity in automatically labeling new sentences and defining the evaluation grid. The tool, in fact, represents the numerical counterpart of the ability of the group to prioritize quality objectives and needs, representing their collective and common knowledge.

3.2.3. MODEL FINE-TUNING PARAMETERS

The values of the hyperparameters were defined according to the dataset characteristics and after a cycle of trial and error (Tab. 3).

Consequently, these are the values of the hyperparameters that allow the obtainment of the best fine-tuned model considering the available dataset.

3.2.4. PERFORMANCE EVALUATION METRICS

Precision, Recall, and F1-score are calculated for each label (Tab. 4).

The performances of the NLP tool in the sentence labeling task seem to be good, showing only two labels with an F1-score value below the threshold of 0.5 and nineteen labels with an F1-score above the threshold. Consequently, the model can be considered properly fine-tuned.

MAX_LEN	TRAIN_BATCH_SIZE	VALID_BATCH_SIZE	EPOCHS	LEARNING_RATE
85	2	32	20	2 E-05

Tab. 3. *Hyperparameters values adopted for the model fine-tuning.*

Metrics	A.1	B.1	C.1	D.1	E.1	E.2	F.1	F.2	G.1	I.1	I.2
Precision	0.71	0.75	0.75	0.56	0.88	0.67	0.68	1.00	1.00	0.67	0.55
Recall	0.92	0.75	1.00	0.42	0.64	0.33	0.77	1.00	0.90	0.67	0.86
F1-score	0.80	0.75	0.86	0.48	0.74	0.44	0.72	1.00	0.95	0.67	0.67
Metrics	**L.1**	**L.2**	**M.1**	**M.2**	**M.3**	**M.4**	**N.1**	**O.1**	**O.2**	**P.1**	
Precision	0.67	0.85	0.67	0.82	0.67	0.64	1.00	0.88	0.44	0.65	
Recall	0.80	0.39	1.00	0.90	0.86	0.60	0.50	0.71	0.78	1.00	
F1-score	0.73	0.54	0.80	0.86	0.75	0.62	0.67	0.78	0.56	0.79	

Tab. 4. *Precision, Recall, and F1-score values per each label.*

4. RESULTS AND DISCUSSION

In the following paragraphs, the fine-tuned NLP tool is applied to new sentences from one of the five available DIPs of *Progetto Iscol@* second phase to evaluate the results of the application of the proposed methodology.

4.1. NLP TOOL SENTENCE LEVEL EVALUATION

In order to demonstrate the tool's ability to translate sentences related to qualitative aspects into numerical values in the context of *Progetto Iscol@*, the developed algorithm was tested on a sample of sentences belonging to a new DIP among the five available. Three examples of the labeling and numerical translation of quality-related sentences are provided in Figure 3.

```
[27] test_comment1 = "Spazi delle aule\
     devono essere aperti, modulabili, facilmente riconfigurabili. L'aula deve diventare uno spazio\
     flessibile e deve adattarsi alle nuove esigenze della didattica che prevede che in questi spazi\
     siano sviluppati lavori di gruppo, interazioni continue con l'insegnante che in questo spazio\
     prepara e verifica la programmazione didattica complessiva"

     _, test_prediction = trained_model(encoding["input_ids"], encoding["attention_mask"])
     test_prediction = test_prediction.flatten().numpy()

     for label, prediction in zip(LABEL_COLUMNS, test_prediction):
       if prediction < THRESHOLD:
         continue
       print(f"{label}: {prediction}")
```

```
I.1 : 0.98
O.1 : 0.97
```

```
[52] test_comment7 = "Lo spazio esterno è parte integrante del progetto e come detto si caratterizza per la\
     presenza di un oliveto: inteso come continuazione ed estensione dello spazio interno, dovrà\
     prevedere un'alternanza tra percorsi e spazi per lo svolgimento di attività all'aperto, essere\
     progettato come luogo privilegiato per il gioco in spazi in ombra e spazi più soleggiati, il\
     movimento, l'apprendimento attivo, l'incontro tra pari e tra i due ordini di scuola, dove\
     sviluppare la consapevolezza dell'importanza di crescere in un ambiente sostenibile e\
     salubre e incrementare comportamenti e stili di vita rispettosi dell'ambiente"

     _, test_prediction = trained_model(encoding["input_ids"], encoding["attention_mask"])
     test_prediction = test_prediction.flatten().numpy()

     for label, prediction in zip(LABEL_COLUMNS, test_prediction):
       if prediction < THRESHOLD:
         continue
       print(f"{label}: {prediction}")
```

```
B.1 : 0.85
E.2 : 0.72
L.2 : 0.72
```

```
[34] test_comment8 = "Rappresenterà il luogo d'incontro privilegiato tra la scuola dell'infanzia e la scuola primaria\
     per le attività legate al Progetto continuità e costituirà lo spazio di mediazione tra il\
     quartiere e la scuola, ambito di possibile socializzazione dei genitori, spazio adeguato per\
     attività extrascolastiche. Sarà uno spazio funzionale ad ospitare manifestazioni, mettere in\
     scena rappresentazioni e organizzare attività laboratoriali, anche sotto forma di grandi tavoli\
     di lavoro, proiezioni di contenuti multimediali."

     _, test_prediction = trained_model(encoding["input_ids"], encoding["attention_mask"])
     test_prediction = test_prediction.flatten().numpy()

     for label, prediction in zip(LABEL_COLUMNS, test_prediction):
       if prediction < THRESHOLD:
         continue
       print(f"{label}: {prediction}")
```

```
A.1 : 0.48
L.1 : 0.67
O.2 : 0.91
P.1 : 0.18
```

Fig. 3. *Example of the programming code developed to process and label three new sentences.*

Labels	A.1	B.1	E.2	L.1	L.2	O.1	O.2	P.1
Confidence sum	0.40	0.05	0.72	1.66	0.72	0.98	0.91	0.10
Criteria weights	7.18	0.95	12.98	29.96	13.00	17.63	16.46	1.84

Tab. 5. *Weights values calculated per each label/criterion according to the NLP outputs.*

Considering only the results of the three sentences from the selected DIP, it was possible to define the evaluation grid customized to the DIP textual content, as shown in Table 5.

The grid obtained through processing the three sentences (Fig. 3) represents the numerical counterpart of the objectives expressed in natural language. The highest weight is obtained by objective L.1, related to integrating space and innovative teaching based on group work and peer learning. Objectives O.1 and O.2, respectively related to space flexibility and extracurricular use (temporal flexibility), get the second and third highest weights. According to the grid, the remaining objectives are sorted as follows: L.2, the openness of indoor space to outdoor space; E.2, the presence of greenery; A.1, the capability of the school building to be used as a Civic Center; P.1, the integration of space and technology and widespread presence of ICT technologies; and, finally, B.1, the visibility and integration of sustainable design choices as an educational medium. The identified objectives and the related weights assigned by the NLP tool seem to reflect the meaning of the sentences used as a sample, confirming the system's ability to identify and translate the objectives, expressed in textual form in the DIP, into a numerical scale of objectives/criteria.

5. CONCLUSIONS AND FURTHER DEVELOPMENTS

The study stands as the first application of NLP methods and tools to documents belonging to the pre-design phase in the Italian construction sector. It demonstrates good levels of precision and recall during the fine-tuning process and useful results in processing samples of textual information derived from a DIP of *Progetto Iscol@* previously excluded from the training and validation datasets of the NLP tool.

The ability of the NLP tool (i.e., a Multi-label Classifier based on the latest language model BERT) to translate DIP quality demands sentences into numerical values to support the definition of an evaluation grid will reduce the possible misinterpretations about the relative hierarchy of the appointing party quality objectives by the design teams and by the external committee. Consequently, the proposed system enables the definition of a common and shared evaluation system fostering a consensus among the involved actors.

Moreover, having been the training dataset definition a group activity, the tool seems to be able to mirror the collective ability, sensitivity, and knowledge of the group of experts involved in the dataset definition. Consequently, the NLP tool can be considered less biased and with a lower grade of subjectivity on the definition of the evaluation grid, being the tool the numerical counterpart of the ability of a group to prioritize quality objectives and needs. These aspects are discussed in more detail in the following chapter.

5.1. FURTHER DEVELOPMENTS

The next step of the research involves measuring the developed system's ability to assign labels/objectives relying on the collective capability of the expert panel and to produce customized evaluation grids for each DIP and, consequently, for each project. For this purpose, two scenarios A and B are proposed.

Scenario A aims to measure the NLP tool's subjectivity degree and capability to represent collective knowledge and intelligence. The NLP tool will process sentences related to the quality objectives, and a weight will be provided for each objective. Firstly, the experts will manually analyze the same sentences, individually providing a weight for each objective. Then the group of experts will perform the same activity collectively. The scores assigned individually, collectively, and by the NLP tool will be compared.

Scenario B intends to evaluate the customization capability of the NLP tool to customize the outputs, mirroring the contents of different DIPs. DIPs of different school buildings (primary and secondary schools) will be processed, and different evaluation grids will be produced using the NLP system. The customized evaluation grids will then be compared with the standardized evaluation grid of *Progetto Iscol@*.

The proposed further developments of the research will further improve the NLP tool, verifying the subjectivity degree and capability of customization employing the two proposed scenarios.

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BUILDING ENERGY CONSUMPTION UNDER OCCUPANTS' BEHAVIOR UNCERTAINTY IN PRE AND POST-RENOVATION SCENARIOS: A CASE STUDY IN ITALY

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Abstract

In Europe, the energy renovation of the existing building stock is a great opportunity to significantly reduce energy consumption and greenhouse gas (GHG) emissions and reach the European sustainability targets. In this framework, building energy simulations (BES) tools are very useful in verifying energy retrofit measures' effectiveness and compliance with national standards. However, an inaccurate numerical prediction, the so-called "performance gap" between measured and numerical performance, is often obtained, mainly due to the inherent uncertainty of model input. Due to its stochastic nature, the occupants' behavior (OB) is considered among the key contributors to this gap. However, the most recent Building Energy Model (BEM) approaches adopt deterministic hourly-defined profiles for characterizing OB, thus neglecting the related uncertainty. In this work, the impact of OB uncertainties on energy consumption (EC) prediction is evaluated by adopting a Karhunen-Loève Expansion sampling technique, used to randomly perturb OB profiles such as heating setpoint (HS), internal thermal loads (IL), and windows opening (NV). Two BEMs of a typical Italian residential building in pre- and post-renovation scenarios are considered and calibrated on real EC data. The results demonstrated that HS uncertainty has the highest impact on EC in all scenarios. Moreover, the higher the energy performance of the building, the higher the impact of OB, especially for IL and NV patterns.

Keywords

Occupants' behavior, Uncertainty analysis, Natural ventilation, Internal loads, Heating setpoint.

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1. INTRODUCTION

In the European Union, 40% of the overall EU energy consumption (EC) and about 35% of the total greenhouse gas (GHG) emissions are attributable to the building sector. This is mainly due to the low energy performance of most of the building stock [1–3], which uses half of this energy for heating households [4]. In the next ten years, the energy demand is expected to increase by more than 20% [5]. Thence, improving the energy performance of these buildings represents an urgent need and opportunity to significantly reduce the European EC and GHG emissions and reach the European sustainability and energy efficiency targets.

In this framework, building energy simulations (BES) are generally used by practitioners to identify the best energy retrofit strategy and to verify its compliance with the requirements set by the National Standards. Still, a discrepancy between the experimental and numerical energy performance called the "energy performance gap" can be found for both new and existing buildings, reaching values up to 250%. This discrepancy can be traced back to the difficulty in obtaining the exact values of all the thousands of inputs needed for characterizing a Building Energy Model (BEM).

Among them, those needed to represent the actual occupants' behavior and interaction with building systems (OB) are generally the most difficult to be defined. This is mainly due to the stochastic nature of the occupants' behavior, especially in residential buildings. Several studies found the occupants' behavior (OB) to be the main responsible for the energy performance gap in residential buildings [6, 7]. Indeed, different occupants' interactions with thermostats, electric appliances, lighting, domestic hot water appliances, and windows may produce a huge difference in building energy consumption, which can be higher or lower than that forecasted by a building energy model (BEM).

Modeling OB can ease the understanding of occupants' impact on building energy use. The more recent Building Energy Performance Simulation (BEPS) tools (e.g. [8]), however, model the OB through deterministic hourly-defined profiles, neglecting the OB's stochastic nature. While simple and easy to understand, this approach does not consider the OB uncertainties, leading to evaluating the energy performance of one of the possible scenarios, which can greatly differ from reality.

The increasing power of the actual computer makes it feasible to conduct parametric BEPS in a reasonable time frame with thousands of simulations and stochastic inputs. As a result, over the past 20 years, the impact of OB uncertainty on building energy use has aroused increasing interest in the research field, where several studies concerning parametric analyses [9, 10] and stochastic OB models [6, 7, 11–13] have been carried out. However, most of these works regard office buildings, while just a few of them focus on residential ones. Moreover, these works mainly investigate the impact of OB on EC by comparing the results obtained through different OB (see e.g. [6]), while few of them consider the inherent uncertainty that can be present in a know, experimentally inferred, OB.

In a common application, indeed, the OB can be qualitatively known since inferred from occupants' interviews. However, this investigation method leads to OBs' patterns characterized by a degree of uncertainty that may affect the reliability of the EC prediction. To consider this uncertainty, O'Neill and Niu proposed an interesting approach based on applying a Karhunen-Loève expansion (KLE) sampling technique [7], which allowed them to consider the spatial and temporal uncertainties of a known OB pattern in BES. In particular, they applied this procedure to a US DOE prototype BEM for modeling the uncertainty of occupants' presence, lighting, heating, and cooling setpoint patterns. However, a very small range of uncertainty of OB (a Coefficient of Variation, CV, of about 3.76%) was assumed, while the uncertainty related to some very important OB, such as windows opening, was neglected [14]. As a result, they found an impact of OB uncertainties on heating consumption of about 4%. Moreover, they conclude that a higher input parameter variation should be used to provide more insights into the impact of different behavior patterns on energy consumption. However, applying this procedure to real residential buildings, calibrated simulations, and window openings is still rare in the literature.

This paper presents an application of the KLE technique to a real, multi-family building in the Italian Marche region (Ancona). A BEM is purposely created and calibrated on observed monthly energy consumption to increase the reliability of the numerical outcomes. Since the impact of OB on EC may vary the buildings' energy performance levels, both pre (calibrated) and post-energy retrofit scenarios are considered. For each renovation scenario, three uncertainty analyses (UA) are carried out by applying the KLE technique to internal loads (IL), heating setpoint (HS), and window opening (NV) patterns. To provide more insights into the impact of different behavior patterns on energy consumption, a higher input parameter variation than that adopted in [7] is considered. In this way, the robustness of EC prediction related to the three different OB pattern uncertainty is examined.

2. PHASES, MATERIALS, AND METHODS

2.1. PHASES

This work can be subdivided into the following three main phases:

- firstly, a BEM of a real residential building is created and enriched through information about OB collected through questionnaires;
- then, to increase the reliability of the numerical results, the BEM is calibrated to real EC data;
- finally, UAs on OB in both pre and post-retrofit scenarios are performed, having the twofold aim of estimating the impact of OB uncertainties on EC before and after energy renovation, and evaluating the energy prediction robustness to OB uncertainty.

2.2. CASE STUDY

A typical Italian multi-family building built between 1970 and 1975 and placed in the hot-summer Mediterranean climate of Ancona, Italy (Csa climatic zone according to Köppen climate classification [15]) has been selected in this study. The building consists of six stories and 12 dwellings, with a floor area for each story of 280.8 m^2 (Fig. 1a). Each floor has three dwellings except for the first floor, which is unheated and below the ground level, and the second and the last floors, which have one and two dwellings, respectively.

For the aim of this study, the dwelling highlighted in Fig. 1b, belonging to the third story, was selected for calibration and UA. The flat consists of two bedrooms, a bathroom, a kitchen, and a living room, and is occupied by three persons, i.e., a couple with one son. The overall area of the apartment is about 80 m^2.

2.3. NUMERICAL MODELING OF PRE- AND POST-RENOVATION SCENARIOS

The building described in Section 2.2 has been modeled through the DesignBuilder ver. 6.1 [16], which is a graphical interface of the EnergyPlus software (see Fig. 2a). The Conduction Transfer Functions (CTF) have been used as heat balance algorithm, while TRAP and DOE-2 as surface convection algorithm for inside and outside convection, respectively. An IdealLoadsAirSystem model was adopted to compute the HVAC heating energy demand with an infinite heating capacity, and an HVAC Coefficient of Performance (CoP) was used to calculate the heating energy consumption from energy demand [17]. Model inputs, such as thermophysical

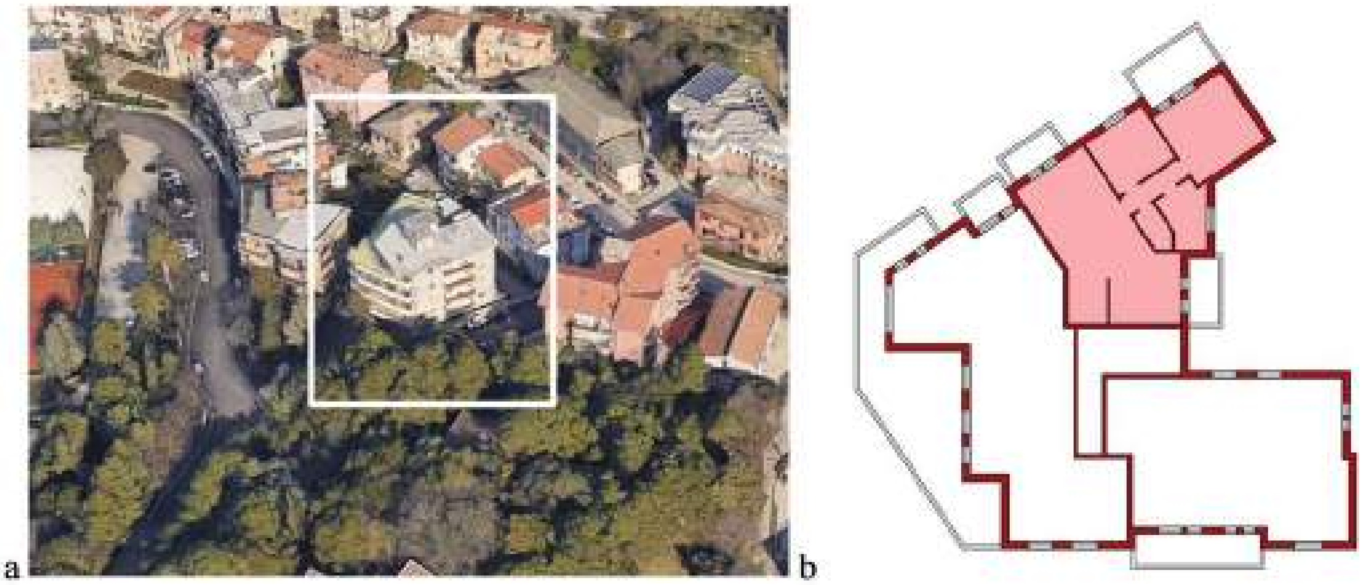

Fig. 1. *(a) Overview of the six-story multi-family building; (b) plan of the third floor with highlighted the case study apartment used for numerical simulations.*

Property	Pre-renovation	Post-renovation
U-value - Exterior walls [W/m² K]	0.65 - 0.90	0.32
U-value - Internal walls between flat and stairs [W/m² K]	0.65 - 0.90	0.32
U-value - Internal walls between rooms [W/m² K]	1.40 – 2.00	calibrated value
U-value - Windows [W/m² K]	1.80 – 2.2	1.20
SHGC [-]	0.65 - 0.85	0.35
Infiltration rate [ACH]	0.30 - 0.50	calibrated value
CoP [-]	0.60 - 0.75	0.85
Heating setpoint - Sleeping area [°C]	18 - 20	calibrated value
Heating setpoint - Living area [°C]	18 - 20	calibrated value
Maximum internal thermal gain [W/m²]	3 - 12	calibrated value
Maximum windows opening area fraction [%]	5 – 100	calibrated value

Tab. 1. *Uniform probability distributions of BEM properties in the pre-renovation scenario and deterministic values in post-renovation scenarios. SHGC: Solar Heat Gain Coefficient; CoP: Coefficient of Performance of the space heating system.*

characteristics of opaque and transparent components, CoP, and infiltration rate, as well as some OB-related inputs, such as maximum internal thermal loads, have been initially estimated from a detailed energy audit, occupants' interview, and literature. Due to the uncertainties in these data, a uniform range of variation has been defined for each relevant property instead of a deterministic value, as summarized in Table 1. These ranges define the search space for the calibration process described in Section 2.4.

Concerning the post-renovation scenario, all the construction elements and heating systems are considered to be upgraded according to the Italian Law on buildings' energy performance [18], significantly improving the thermal performance of the entire building. The deterministic input values considered for the post-renovation scenarios are summarised in Table 1.

The patterns related to the interactions between occupants and building systems, i.e., ILs, HS, and NV, have been inferred from questionnaires submitted to the occupants. The obtained information has been then translated into the estimated daily profiles shown in Fig. 2b, c and d. These data have been used as a starting point for BEM calibration (Section 2.4) and UA (Section 2.5). Concerning the ILs, the pattern in Fig. 2a is multiplied by a maximum value to obtain the related hourly value of ILs, whose range of variation is indicated in Table 1 [19, 20]. Regarding the HS, two different thermostats are in the apartment, i.e., one in the sleeping area and one in the living area. Then, according to occupants' information, two different heating activation profiles were considered, which were multiplied by a different HS. Finally, the NV schedules reported in Fig. 2d indicate the time when the occupants open the windows to ventilate the apartment. According to the ASHRAE book of fundamentals [8, 21], the resulting flow rate from windows is then computed through a superposition process as the combined effect of the airflow driven by wind (Q_W) and the airflow due to stack effects (Q_S). In particular:

$$Q_W = C_W A_0 V \qquad (1)$$

$$Q_S = C_D A_0 \sqrt{2gh|T_Z - T_O|/T_Z} \qquad (2)$$

where C_W is the opening effectiveness computed as reported in Eq. 3 [8, 21]; A_0 is the opening area of windows, which is unknown and then will be defined in the calibration phase (a range between 10 and 100% of the total opening area is assumed, see Tab. 1); V is the external wind speed; C_D is the discharge coefficient equal to 0.4 + 0.0045|T_Z-T_O|; g is the standard gravity; h is the height from the midpoint of the lower opening to the neutral pressure level; T_Z and T_O are the internal and external air dry-bulb temperatures, respectively.

$$C_W = 0.55 - 0.25|Angle\ difference|/180 \qquad (3)$$

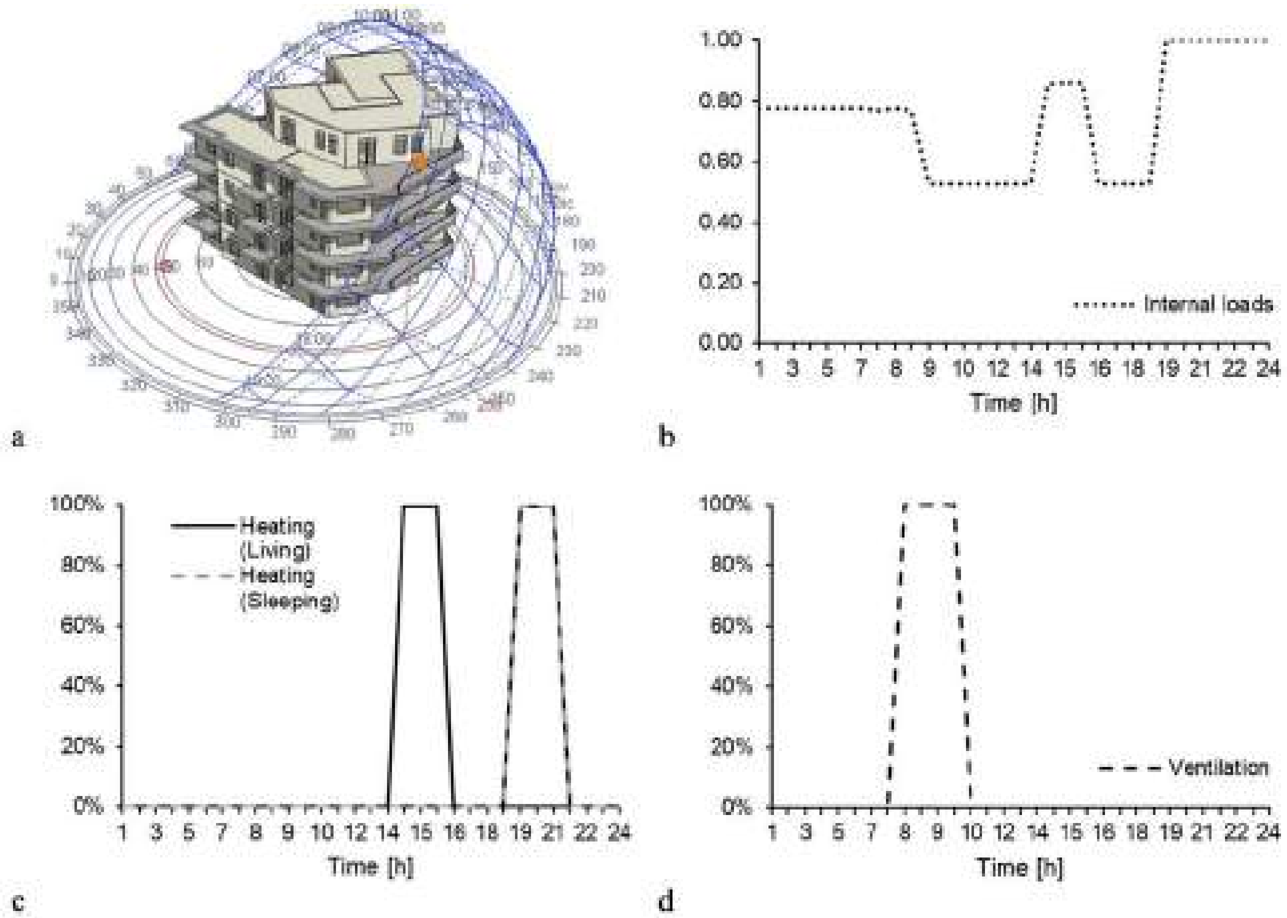

Fig. 2. *(a) BEM of the residential building; (b) OB's patterns for internal gains; (c) OB's patterns for heating; (d) OB's patterns for natural ventilation inferred from occupants' questionnaires.*

2.4. MODEL CALIBRATION

BEMs generally provide inaccurate numerical predictions if not calibrated or validated on real data [22]. Despite this, uncalibrated BEMs are often used in the literature to address the impact of OB on EC [7, 11]. To increase the accuracy of the numerical predictions, the developed BEM has been calibrated against monthly energy consumption in this study, as requested by relevant international Standards on BEM calibration [23]. The selected baseline period for data collection and simulation goes from the 1st of November 2016 to the 24th of March 2017, corresponding to the period during which Italian national authorities allow space heating in Ancona, Italy, i.e., where the building is located. During this period, weather data such as the outdoor air temperature, relative humidity, horizontal global solar radiation, wind velocity, and direction were collected through a weather station placed 1 km away from the building.

An automated calibration tool purposely developed by the authors and based on Artificial Intelligence optimization algorithms has been used to perform the BEM calibration. In particular, the Non-dominated Sorting Genetic Algorithm (NSGA-II) has been implemented for the optimization process, which is one of the most used and efficient for automatic BEM calibration [24]. The tool automatically searches the set of input data that minimizes the error between simulated and measured time-series data, given a search space defined by the input ranges of variation.

Two error functions can be used for assessing the error, i.e., the Coefficient of Variation of the root mean square error (CVRMSE) and the Normalized Mean Bias Error (NMBE). According to the ASHRAE guideline 14 [23], a model is considered calibrated on monthly energy consumption when the CVRMSE and NMBE are below or within specific thresholds, equal to 15% and ±5%, respectively [23].

2.5. UNCERTAINTY ANALYSES

Three distinct "local" uncertainty analyses (UAs) have been carried out on the pre-renovation and post-renovation scenarios to evaluate the impact of OB uncertainties on building EC and then the robustness of the calibrated BEM energy prediction to OB. Each UA concerns the variation of one of the estimated OB patterns shown in Fig. 2b, c, and d, i.e., the internal load pattern (IL-UA), the heating setpoint pattern (HS-UA), and the natural ventilation pattern (NV-UA), respectively. The pattern variation is obtained by adopting the Karhunen-Loève expansion (KLE) sampling technique, which has been successfully used in the literature to evaluate the impact of OB on EC [7, 25].

Similar to the Fourier analysis, a KLE allows representing a stochastic process as an infinite linear weighted combination of orthogonal functions, reducing its dimension by converting time-dependent uncertainty into time-independent stochastic parameters. In practice, the KLE represents a stochastic process x(t) through the following equation:

$$x(t) = \mu_x(t) + \sum_{i=1}^{\infty} \sqrt{\lambda_i}\psi_i(t)y_i \tag{4}$$

where $\mu_x(t)$ is the mean value at the time t, $\psi_i(t)$ is a temporal basis function, and λ_i and y_i are the eigenvalues and eigenfunctions of the covariance function $C(x_1, x_2)$. In particular, y_i is a time-independent stochastic parameter expressed as Gaussian variables characterized by an average equal to zero. The most used types of correlation functions are Gaussian, exponential, or turbulent functions [26]. In this study, the following exponential covariance function is adopted:

$$C(x_1, x_2) = c\, e^{-\left(\frac{x_1 - x_2}{5}\right)^2} \tag{5}$$

where *c* is a variance scaling parameter corresponding to the Coefficient of Variation (CoV) of each normally distributed hourly value. A different value of c has been adopted for the different OB patterns. Being ILs and NV characterized by high uncertainty, a high value of *c*, equal to 20%, has been assumed in these cases. Conversely, a smaller *c* value (2.5%) has been considered for the HS-UA to have plausible values for hourly HS, corresponding to a maximum deviation of ±1°C from the calibrated value.

Assuming that $\mu_x(t)$ is equal to 0, the KLE is used in this work to obtain 1000 sets of 24 "hourly" random coefficients, as shown in Fig. 3a. The sample dimension is chosen to ensure the convergence of the UA result. These coefficients are then used for computing 1000 new hourly patterns for each UA according to the following formulation:

$$X^*(t) = X(t) \cdot \left(1 + x(t)\right) \tag{6}$$

where $X(t)$ is the estimated OB pattern, while the $X^*(t)$ represents the perturbed one. In Fig. 3b, the 1000 patterns obtained for the IL are plotted as an example.

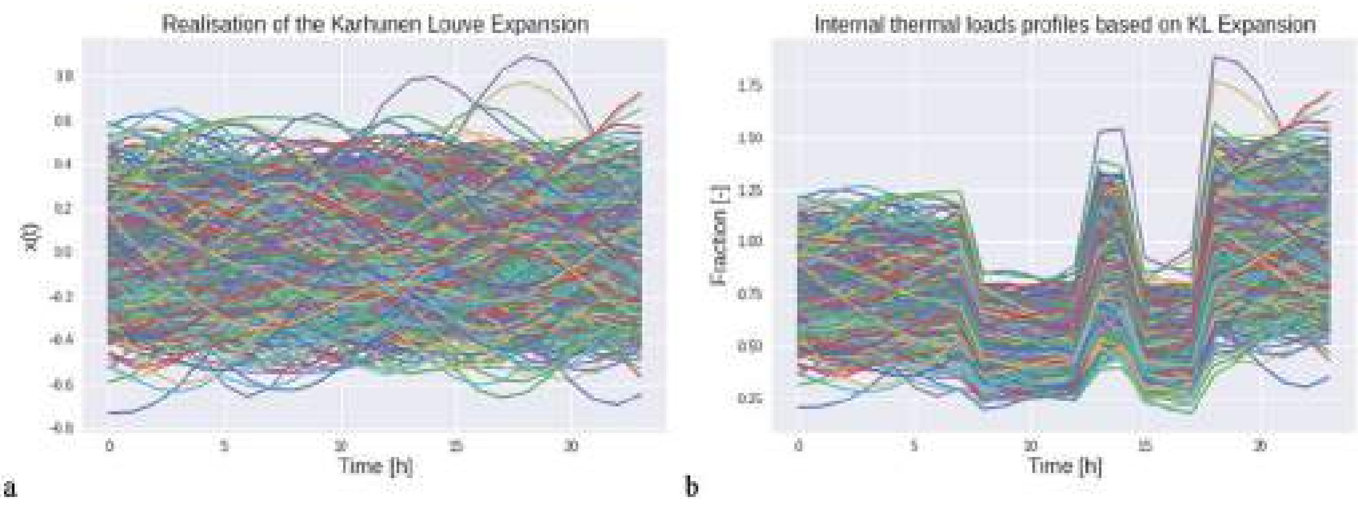

Fig. 3. *(a) 1000 realizations of the KLE; (b) exemplary application of the KLE technique on the internal thermal loads' estimated profile.*

3. RESULTS AND DISCUSSION

3.1. MODEL CALIBRATION

This section reports the results of the model calibration used to increase the reliability of numerical prediction. Figure 4 shows a comparison between observed and predicted EC after BEM calibration, while the calibrated values of the model inputs are reported in Table 2.

The automated calibration tool allowed for reaching a good match between experimental and numerical data. Overall, the obtained CVRMSE and NMBE values are equal to 13.57 and -3.56%, respectively, i.e., lower than the thresholds set in the international Standard to consider a BEM calibrated (equal to 15 and ±5%, respectively, according to the ASHRAE guideline 14 [23]). The obtained model can then be used for reliable EC prediction in both pre and post-renovation scenarios since it represents the actual energy performance of the building [23]. Since observed data are obtained from energy bills and predicted data (from calibrated simulations) are deterministic values, it should be noted that measurement accuracy and confidence interval of numerical predictions cannot be determined in this case.

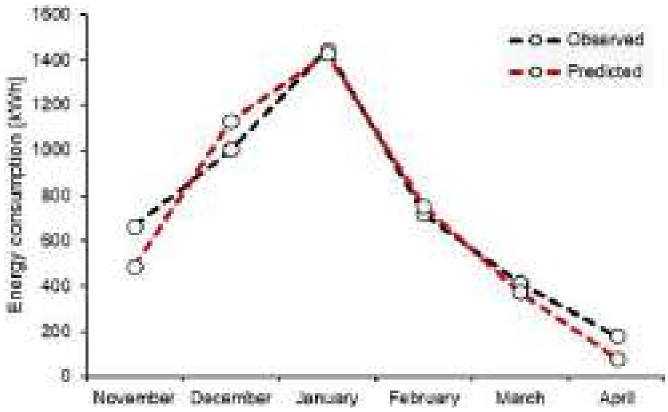

Fig. 4. *Comparison between predicted and observed EC for space heating after BEM calibration.*

3.2. UNCERTAINTY ANALYSIS IN THE PRE-RENOVATION SCENARIO

Starting from the calibrated BEM, a KLE-based UA has been carried out for each considered occupants-related profile, i.e., internal loads (IL-UA), heating setpoint (HS-UA), and natural ventilation (NV-UA). The results of the IL-UA, HS-UA, and NV-UA are reported in terms of yearly EC distribution (Fig. 5a) and monthly EC (plume graph in Fig. 5b). A comparison between calculated and measured monthly EC is also shown in Fig. 5b. It should be noted that only occupants related parameter are varied in the uncertainty analyses carried out in this study since other uncertainty parameters (e.g., building envelope features) have been fixed to deterministic values through the calibration process (see Tab. 2). This allowed us to focus our work on the impact of OB only on numerical results.

For each UA, the yearly EC can be considered normally distributed, characterized by a mean value of

Input parameters	Calibrated values
U-value - Exterior walls [W/m² K]	0.66
U-value - Internal walls between flat and stairs [W/m² K]	0.67
U-value - Internal walls between rooms [W/m² K]	1.43
U-value - Windows [W/m² K]	1.96
SHGC [-]	0.65
Infiltration rate [ACH]	0.31
CoP [-]	0.75
Heating setpoint - Sleeping area [°C]	18.1
Heating setpoint - Living area [°C]	20.0
Maximum internal thermal gain [W/m²]	7.37
Maximum windows opening area fraction [%]	0.06

Tab. 2. *Calibrated values for the pre-retrofit scenarios.*

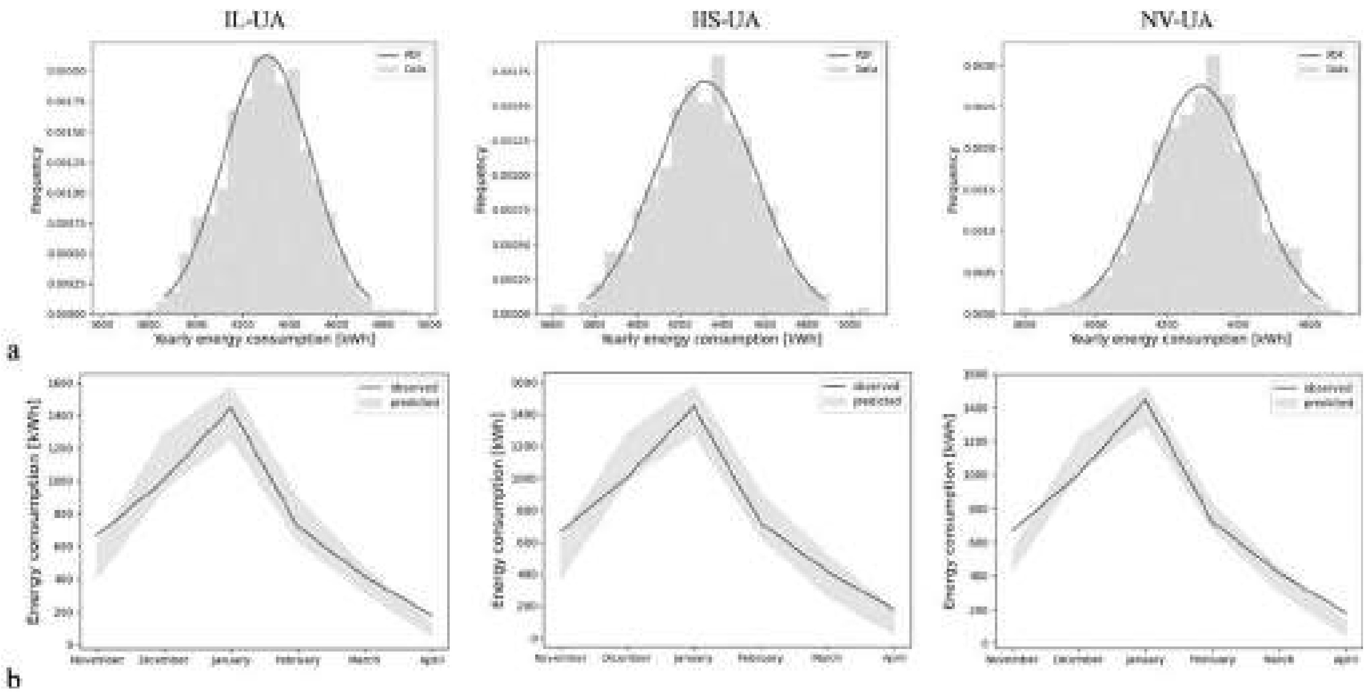

Fig. 5. *(a) Yearly and (b) monthly EC for the three UAs in the pre-renovation scenario.*

about 4300 kWh. Some differences can be noted in terms of standard deviation, equal to 236.5, 189.2, and 141.9 kWh, for HS-UA, IL-UA, and NV-UA, respectively, corresponding to a CoV, equal to 5.5, 4.4, and 3.3%. Thence, in the pre-renovation scenario, the HS schedule uncertainty has the highest impact on the EC, followed by IL and NV uncertainties.

Considering the lower variability assigned to the HS pattern (CoV = 2.5%) compared to that assigned to the IL and NV ones (CoV = 20%), the larger CoV of EC prediction obtained in the HS-UA denotes a high impact of the HS pattern on EC. Conversely, the lower CoVs of EC obtained for IL-UA and NV-UA indicate the lower importance of IL and NV patterns. These results are similar to those obtained in other works. In [7], for example, the author obtained a higher impact of HS pattern uncertainty than that obtained for ILs for office buildings. However, it should be noted that comparing the results among different studies is not an easy task due to the differences that can be found in building characteristics, type of use, OB patterns, and location. This notwithstanding, it can be stated that a correct characterization of the HS profile can be considered fundamental for obtaining realistic predictions of EC in existing buildings with low energy performance.

3.3. COMPARISON BETWEEN PRE AND POST-RENOVATION SCENARIOS

In order to evaluate how the impact of OB on EC may vary from a pre-renovation to a post-renovation scenario, the same three UAs considered in Section 3.2 have been replicated but by considering an improved energy performance of the same case study (see Tab. 1). In Figure 6, the results of the two scenarios are plotted and compared in terms of box plots of yearly energy consumption.

The first evident results regard the expected reduction of the yearly building EC for all the considered UA, which pass from an average of about 4300 kWh in the pre-renovation scenario to about 2800 kWh in the post-renovation, corresponding to a decrease in EC of about 35%. The standard deviation values of the three EC samples are equal to 187.0, 168.5, and 154.0 kWh for HS-UA, IL-UA, and NV-UA, respectively, corresponding to a CoV equal to 6.6, 6.0, and 5.5%. These values are higher than that obtained in the pre-renovation scenarios. The increase obtained in terms of CoV is mainly due to the lower average value of yearly EC, but they differ among different UAs. In particular, the highest increase is obtained for the NV (+67%), followed by the IL and HS (+36% and +20%, respectively). This indicates

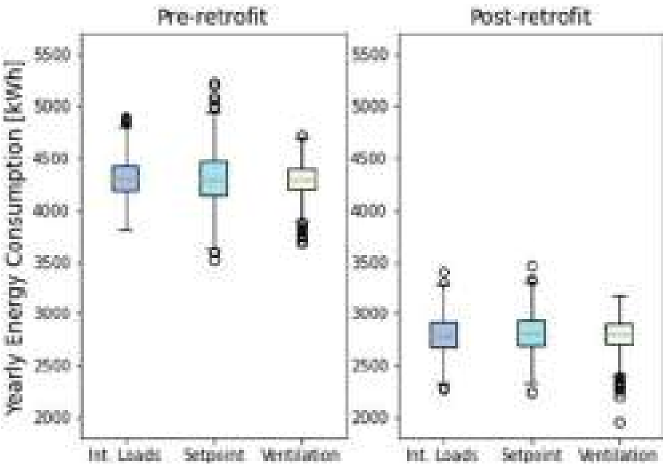

Fig. 6. *Box plot of yearly EC in pre- and post-renovation scenarios.*

that higher building performance can lead to a higher impact of OB uncertainties, particularly those related to heat gains or losses that remain quite constant after renovation, such as internal loads and air changes. Then, this result highlights that the higher the performance of the building, the higher the importance of IL and NV uncertainties in simulations.

4. CONCLUSION

This work allowed us to investigate the impact of uncertainties of known occupants' behavior (OB) information on the energy consumption (EC) of a real existing residential building located in Italy in both pre and post-renovation scenarios. At this aim, a BEM model is created and calibrated on real monthly energy consumption data to increase the accuracy of the numerical prediction. Then, three uncertainty analyses are carried out by expanding, one at a time, occupants' behavior uncertainties related to internal loads (IL), windows opening/natural ventilation (NV), and heating setpoint (HS) patterns through the KLE sampling technique. A pre and post-renovation scenario is also considered to evaluate how the impact of occupants' behavior on energy consumption may change to vary building energy performance levels.

Results demonstrated that the HS uncertainties always have the highest impact on EC regardless of the energy performance level of the building, followed by IL and NV. In particular, the low uncertainty assigned to the HS variation has always led to the largest CoVs of EC, denoting the high importance of the HS pattern uncertainty, regardless of the energy performance of the building. Conversely, the high uncertainty of the IL and NV patterns, and the obtained low variation on EC, denote a low impact of IL and NV uncertainties on EC, especially for the pre-renovation scenario. However, when the energy performance of the building is increased, the importance of IL and NV uncertainties in simulations increases accordingly. Thus, the uncertainty in IL and NV should be accurately considered in high-energy performance buildings.

The main limitation of this work lies in the use of a local UA approach. Thence, further studies are needed to evaluate the overall EC probability distribution by varying all the occupants' patterns. Moreover, more climatic locations and building use/type scenarios should be considered to draw more general conclusions.

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ECOLOGICAL TRANSITION FOR THE BUILT ENVIRONMENT: NATURAL INSULATING MATERIALS IN GREEN BUILDING RATING SYSTEMS

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Abstract

The regenerative concept of design and construction is gaining relevance, as it is changing the sustainability paradigm toward the ecological transition for the built environment, representing a track on which economic and financial support policies are currently being routed. One of the ways to achieve ecological transition is to use sustainable insulating materials in buildings. In addition, certification systems have been developed to actualize and renovate the concept of sustainability. The literature review showed that no studies deal with the influence of different insulating materials on green building rating systems. This research applies ITACA and LEED protocols to quantify the impact of insulating materials on certification levels. Starting from the comparison between these protocols and the analysis of credits related to sustainable building materials within LEED, the rating systems were applied to an existing multi-story residential building by varying the insulating materials for the building envelope, such as glass wool, expanded polystyrene (EPS), and two types of natural materials (e.g., mineralized wood fiber and kenaf). The results showed that every envelope configuration obtained the certification in both protocols, except EPS, which did not obtain the certification in LEED. However, although kenaf and mineralized wood fiber can be considered sustainable materials, they do not reach the maximum achievable category score influenced by the insulating material choice.

Keywords

LEED, ITACA, Renovation project, Sustainable envelope, Environmental protocols.

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1. INTRODUCTION

The conventional building design and construction process negatively impact the environment and natural resources [1]. With the current development speed of contemporary society, these issues cannot be fully addressed with the traditional concept of sustainability, which is primarily concerned with reducing environmental harm. Thus, regenerative design and construction are gaining relevance, as it is changing the sustainability paradigm toward the ecological transition for the built environment and the delivery of a human-centric environment, coupled with the circular economy, which aims to ensure the natural environment is renewed, restored, and revitalized [2]. In order to take these elements into account, a more thorough and integrated approach is needed, which allows for defining buildings' global efficiency. Energy and environmental certifications support this process and allow for building assessment in terms of energy consumption and efficiency and their impact on the environment and human health [3].

As new buildings are characterized by reduced operating energy utilization, additional consideration should be given to the embodied elements, e.g., the Embodied Energy and the Global Warming Potential (GWP) because of construction materials and systems [4, 5]. Embodied effects are the ecological burdens created by the purchase of raw materials, their handling, production, moving to location and construction during the entire lifetime. Embodied elements are important in energy-efficient constructions as demonstrated by several researchers: incorporated impacts are a percentage of the overall equal to 45% in [5], 50% in [6], and 57–74% in [7]. In several cases, burden shifting can also be produced, and LCA is a valuable method of assessment to avoid it [8, 9].

In general, two approaches exist in assessing building sustainability [10]. The qualitative or score-based method relies on certain requirements corresponding to weights and scores, the total sum of which indicates the level of building energy efficiency and environmental sustainability. These score-based assessment tools responded in a simple, accessible, and easily replicable way to the needs of the market and industry professionals. Differently, the quantitative method is related to LCA (Life Cycle Assessment), which quantifies the environmental impact of several indicators, including energy used by the building in its life cycle. Therefore, it is a rigorous environmental analysis of the entire construction process, including building management and end of life. For this reason, a recent study conducted by Tagliabue et al. [11] defined that the most influential rating systems worldwide available for building sustainability assessment (e.g., LEED, BREEAM, etc.) updated their checklists, including criteria related to the reduction in energy for extraction, production and materials transportation on the field.

Certification systems were developed globally to actualize and renovate the concept of sustainability degree [12]. Among the voluntary protocols around the world, including Building Research Establishment Environmental Assessment Method (BREEAM, UK), *Deutsche Gesellschaft für Nachhaltiges Bauen* (DGNB, Germany), *Haute Qualité Environnementale* (HQE, France), Green Star Rating Tools (Green Star, Australia) and *Istituto per l'innovazione e Trasparenza degli Appalti e la Compatibilità Ambientale* (ITACA, Italy), the most used and widely recognized is Leadership in Energy and Environmental Design (LEED, USA). Many studies were carried out to analyze and compare different methodological approaches to green rating systems. At the end of this study, the analysis of previous research comparing LEED and ITACA is reported. Asdrubali et al. [13] proposed a comparative study between these two building environmental assessment methods applied to two residential buildings located in Italy. The authors demonstrated that there are no important technical differences between the two certification methods since the common scientific basis in both cases follows international standards and regulations. Buffoli et al. [14], after a deep analysis of the state of the art focusing on the previously mentioned evaluation systems, identified the main strengths and weaknesses of such tools concerning Sustainable Healthcare's project final objective. The authors concluded that both systems lack a multidisciplinary approach and the consideration of all three spheres of sustainability, not including, for instance, user-centrality, health outcomes, or managerial issues. Finally, Mattoni et al. [15] investigated the differences and similarities between LEED and ITACA. This allowed for the understanding of which factors most influence the final performance rate of each system and provided useful suggestions for improving the existing protocols.

Since the built environment contributes about 40% of global carbon emissions, and emissions embodied in building materials and construction contribute about 11% of global emissions (as much as all automobiles), it is up to architects and other building professionals to reduce harm, and, when possible, contribute to environmental regeneration and restoration [16, 17]. In order to achieve these objectives, one of the ways is to use sustainable materials for building construction projects [18]. Regarding the sustainable properties of materials used in green buildings, it is necessary to check whether they are renewable, reusable, or recyclable [19]. Renewable materials can be manufactured or generated quickly enough to keep pace with the use speed. These materials can be derived from natural or synthetic products and often include recycled components. They could also be from natural, renewable sources such as plantation forests and those made from agricultural waste products. The reuse potential of a construction material is another criterion by which the sustainable property of a material could be analyzed. Reusing a certain material means using it again for the same purpose that it was originally made for or an entirely different purpose (adaptive reuse). Reusing building materials ensure they do not become waste and end up in landfills. Salvaged, refurbished, and reused materials can all contribute to reducing the demand for virgin materials. Finally, recyclable materials, components, and assemblies play a significant role in conserving limited and depleting resources while eliminating waste from landfills.

Various previous research is aimed at evaluating the ability of alternative insulation materials, although their usage is still limited. The interest is in naturally derived materials, normally realized from agricultural residues [20] or waste recycling [21]. Other works have previously obtained data regarding Embodied Energy and GWP of plants or animal-developed insulation boards: Asdrubali et al. [22], for example, suggested a study on the acoustic, thermal, and environmental characteristics of alternative natural insulation materials; Schiavoni et al. [23] examined the thermal, acoustics, environmental, fire and water vapor resistance of conventional, natural, and advanced insulation materials. It was demonstrated that some natural materials (e.g., cork) have elevated Embodied Energy and GWP, while some commercial materials, such as stone wool, showed great environmental characteristics with decreased Embodied Energy and GWP.

While there was a wide range of research mainly focused on the energy use and emission production during the operation phase of LEED-certified buildings and on the analysis of the weight of specific items on the environmental rating assessment [24], research on the role of building envelope materials in green rating systems considering the environmental aspects is a growing field of interest. Yu et al. [25] compared the bamboo-structure building with an alternative brick-concrete building to distinguish the intrinsic differences between Embodied Energy and carbon emission. The authors conducted a comprehensive life cycle assessment along material flows based on technical potentials and the current LEED standard. Alshamrani et al. [26] developed an integrated LCA-LEED model for the enhanced sustainability assessment of structure and envelope types of Canadian School Buildings. Various combinations of structure-envelope options are tested by using concrete, masonry, steel, and wood as structural materials, and precast panels, steel stud, wood stud, and cavity wall as envelope systems by considering all the life cycle phases for a life span of 75 years.

The literature review showed that no studies deal with the influence of different insulating materials on green building rating systems, especially when natural materials are used to reduce environmental impacts. In addition, most of the previously described studies evaluated and compared different protocols only from a theoretical point of view without considering real case studies, mainly focusing on new construction building projects. In order to fill these knowledge gaps, this research aims to apply ITACA (the most used protocol in Italy) and LEED (the most used protocol worldwide) to quantify the impact of natural insulating materials on the certification levels. After a major renovation intervention, an existing Italian residential building was chosen as a case study to validate the methodological approach. The sustainability rate was evaluated by simulating different insulating materials applied to the external surface of the building envelope: e.g., glass wool, expanded polystyrene (EPS), and two types of natural materials (mineralized wood fiber and kenaf). Due to national incentives, installing the thermal insulation layer on the external wall surface is the most common technique currently used in Italy for building energy renovation. Therefore, this case study is representative of the existing buildings undergoing renovation interventions.

2. METHODOLOGY

The categories and credits influenced by the variation of building materials were analyzed for ITACA and LEED to evaluate the impacts on the partial (single category) and final scores. Starting from the comparison between the protocols using the approach developed by Asdrubali et al. [13] and the analysis of prerequisites and credits driving the use of sustainable building materials within LEED, the two different rating systems were applied to an existing multi-story residential building located in Catania, Sicily, by varying the insulating material for the building envelope.

2.1. LEED AND ITACA SYSTEM COMPARISON

For the description of the protocol structure, refer to the technical guidelines. LEED categories related to building materials are "Energy and Atmosphere" (EA), "Materials and Resources" (MR), and "Indoor Environmental Quality" (IEQ) (Tab. 1). The first category includes the "Optimization of energy performance" parameter influenced by the variation of insulating materials and allows a maximum of 27 points over the total category score equal to 30. Therefore, it strongly weighs on both the partial category score and the final score. Most of the parameters included in the MR category are affected by the change of insulating material, having a high impact on the partial category score, counting up to 10 points over the total category score equal to 15, and, therefore, they have a remarkable impact on the final score. These parameters are described in the next paragraph. Focusing on the IEQ category, only the "Acoustic" parameter is influenced by the variation of insulating materials, counting up to 2 points over the total category score equal to 20, so it has a not significant impact on both the partial category and final scores (up to 100). Therefore, the impact of the insulating materials on the acoustic performance was neglected.

Among ITACA categories, the ones influenced by the change in insulating materials are "Resource Consumption" (RC) and "Indoor Environmental Quality" (IEQ) (Tab. 2). Unlike LEED, the RC category includes building energy performance and materials parameters. This category counts for 53.60% of the final score. Insulating material variation influences five of the nine parameters, accounting for 29.40% of the total score. Like LEED, the IEQ category is affected by insulating material change, impacting the partial category score of 18.20% and the total score of 4.55% through the "Acoustic insulation of building envelope" parameter. In this case, too, this parameter was neglected.

The comparison between the two methods was developed based on the procedure described by Asdrubali et al. [13]. By observing Table 1 and Table 2, it is easy to notice the differences between the macro-areas of LEED and ITACA protocols because they are not defined in the same manner; thus, comparing results is difficult. In order to make the two methods comparable, the common items included in each LEED and ITACA category were identified to define five macro areas: Site, Water, Materials, Energy, and Indoor Environmental Quality. Refer to Asdrubali et al. [13] for more information about parameters included in LEED and ITACA categories and how they were grouped to create the new macro areas.

The scores obtained in Site, Water, and Indoor Environmental Quality categories are not influenced by the change in insulating materials. However, these categories were analyzed to evaluate the effect of the building renovation project on the partial score related to these categories compared to the total achievable score. Table 3 shows the new distribution of the parameters into five categories, highlighting the differences between the scores achievable with LEED and ITACA.

LEED categories	Maximum score
Sustainable Sites	23
Water Efficiency	12
Energy and Atmosphere	30
Materials and Resources	15
Indoor environmental quality	20
Total	**100**

Tab. 1. *Areas and scores of LEED certification.*

ITACA categories	Maximum score
Site quality	4.0%
Resource consumption	53.6%
Environmental loads	17.5%
Indoor environmental quality	18.2%
Service quality	6.7%
Total	**100%**

Tab. 2. *Areas and scores of ITACA certification.*

System	Site	Water	Materials	Energy	Indoor Environmental Quality	Total
LEED	23	12	15	30	20	100
ITACA	4,3	18,2	10,4	47,6	19,5	100

Tab. 3. *New macro-areas and scores for LEED and ITACA.*

2.2. "MATERIALS AND RESOURCES" CATEGORY IN THE LEED PROTOCOL

Within the MR category in LEED rating systems, some prerequisites and credits drive sustainable building materials' use. They include, amongst others, storage and collection of recyclables, building life cycle impact reduction, and sourcing of raw materials.

2.2.1. STORAGE AND COLLECTION OF RECYCLABLES

Storing and collecting recyclables is a mandatory requirement in LEED. The intent is to reduce the landfills and incinerators burden generated when building occupants haul and dispose of waste through reduction, reuse, and recycling service and education. The approach involves providing dedicated areas accessible to waste haulers and building occupants to collect and store recyclable materials for the entire building. Recyclable materials must include mixed paper, corrugated cardboard, glass, plastics, and metals. Access to the recycling location should be as convenient as possible to ensure employees participate in the recycling program.

2.2.2. BUILDING LIFE CYCLE IMPACT REDUCTION

This LEED credit intends to encourage adaptive reuse and optimize material environmental performance. The aim is to demonstrate the reduction in environmental impacts during initial project decision-making by reusing existing building resources or reducing materials use through life cycle assessment. The first approach involves maintaining the existing building structure, envelope, and interior non-structural elements. Materials reused or recovered off-site and incorporated into the building can also contribute to the calculation of credits. The whole-building approach to credit involves cradle-to-grave life cycle assessment of the designed building structure and envelope.

2.2.3. SOURCING OF RAW MATERIALS

This credit requirement encourages the use of products and materials for which life cycle information is available, and they have environmentally, economically, and socially preferable life cycle impacts. Project teams are rewarded for selecting products that are extracted or sourced responsibly. Some LEED practices encourage responsible sourcing of raw materials, including extended producer responsibility, use of biobased products, use of certified wood, and reuse and recycling of materials.

2.3. "ECO-FRIENDLY BUILDING MATERIALS" CATEGORY IN THE ITACA PROTOCOL

ITACA indicates the characteristics of "eco-friendly building materials". The ones usually deemed eco-friendly are not toxic, reusable, renewable, recycled, or locally found.

ITACA encourages the reuse of materials or the usage of recycled materials. Hence the criteria: Recycled/Salvaged Materials intends to assess the percentage of recycled/salvaged material that is required. Additional points are allocated when materials are derived from renewable resources, that is, those products whose makeup partially comes from plants or animals.

The supply of building materials from local manufacturers reduces the distance of the route that a certain element takes to reach the construction site. This would help decrease the emissions generated during the transport of the material. To determine this indicator, "locally sourced material" is considered, meaning a distance of 300 km from the location. In addition, the percentage of components treated with ornamental materials of regional manufacture is considered, i.e., materials produced within a distance of 150 km. One more criterion is "eco-sustainable materials", which determines the percentage of eco-sustainable materials, i.e., construction materials whose eco-friendly attributes are accredited.

2.4. CASE STUDY

A building constructed in the early 1970s was chosen to represent typical multi-story residential buildings in European cities undergoing energy renovation intervention. This study was developed in the city of Catania,

Fig. 1. *Aerial view of the urban area where the reference building is located (Catania, Italy).*

Southern Italy (37.52° N, 15.07° E). The Mediterranean climate typical of this geographical area is characterized by hot summers and mild winters. The case study used as a reference consists of a seven-floor multi-story building, a widespread type in the densely urbanized area close to the city center of Catania (Fig. 1) and, therefore, located near the mass transport systems. Each floor consisted of two residential apartments (Fig. 2). The structure of the building is reinforced concrete, while the floors are reinforced concrete with hollow bricks.

The building walls are described in Table 4. This type of vertical envelope, widespread in buildings belonging to the same period, is characterized by low thermal performance (U-value 0.975W·m^{-2}·K^{-1}). Single transparent

Fig. 2. *Typical floor distribution (on the left) and perspective view (on the right).*

panes of glass were used with a thickness of 3mm and thermal transmittance Ug=5.89W·m^{-2}·K^{-1}. The window frame was aluminum without a thermal break and with a thermal transmittance of UF=5.88W·m^{-2}·K^{-1}. The overall thermal transmittance U of the existing flat roof was 1.12W·m^{-2}·K^{-1}.

Apart from the thermal insulating material applied to the external wall surfaces (without changing windows), the energy renovation project concerns the installation of a new and high-efficiency heating system in each apartment, photovoltaic panels, electric charges for cars, and a new elevator. No interventions were designed to improve the water supply's efficiency and reduce water consumption.

The energy performance assessment in LEED is based on the whole building's performance, involving a dynamic simulation. In this paper, DesignBuilder with EnergyPlus engine was utilized. LEED requires to exhibit a percentage increase in the energy performance of the analyzed building, compared to the evaluation of energy utilization of a reference building. The latter should be modeled following the creation of a prototype described in Appendix G of ASHRAE 90.1-2007 [27] with some modifications to adjust the model to the Italian condition. The comparison among the energy performance of the analyzed building and the reference one has to exhibit an increase of a minimum percentage of 10%; it is possible to achieve the highest result demonstrating an increase of 66%.

In ITACA, the energy performance evaluation is separated into four sheets that assess the thermal transmittance of the envelope, the primary energy for heating, the net energy for cooling, and the CO_2 emissions that need computations based on the method defined by the UNI TS 11300: 2008 [28].

The important difference between ITACA and LEED lies in the method: the tool sheets need specific outcomes resulting from a simulation of the projected building, while LEED necessitates the simulation of two models, one corresponding to the real building and the other with features established by the Appendix G of ASHRAE 90.1-2007 [27].

Material	Thickness [mm]	Oven Dry Density [kg·m^{-3}]	Thermal Conductivity [variable]	Specific Heat [kJ·kg^{-1}·K^{-1}]	Thermal transmittance [W·m^{-2}·K^{-1}]
Plaster	20	1860	λ = 0.72 W·m^{-1}·K^{-1}	0.84	36.00
Hollow brick	120	-	R = 0.31 m^2·K·W^{-1}	-	3.23
Air gap	60	-	R = 0.18 m^2·K·W^{-1}	-	5.55
Hollow brick	120	-	R = 0.31 m^2·K·W^{-1}	-	3.23
Plaster	20	1860	λ = 0.72 W·m^{-1}·K^{-1}	0.84	36.00

Tab. 4. *Stratigraphy of the existing external wall in the case study building.*

2.5. INSULATING MATERIALS

Table 5 shows the insulating material properties of the building envelope, e.g., glass wool, expanded polystyrene (EPS), mineralized wood fiber, and kenaf, as identified by Schiavoni et al. [23] because they have comparable thermal conductivities but diverse environmental characteristics: EPS has higher embodied energy than the glass wool, while wood fiber and kenaf have lower embodied energy. These insulating materials are applied to the external surface of the existing building envelope, which is the most common technique for existing building retrofitting in the Italian context.

Material	Density [kg·m^{-3}]	Specific heat [kJ·kg^{-1}·K^{-1}]	Thermal conductivity [W·m^{-1}·K^{-1}]
Glass wool	21	1.0	0.035
EPS	22	1.3	0.035
Mineralized wood fiber	533	1.8	0.065
Kenaf	100	1.7	0.030

Tab. 5. *Insulator input data used for thermal calculation of the case study.*

The first material, glass wool, is produced by mixing natural sand and glass (usually recycled). The transformation in fibers occurs thanks to centrifugation and blowing processes. Then, the fibers are bounded thanks to the addition of resins. Several studies demonstrated that the thermal insulation performance of glass wool materials for building applications seems to be not affected by high temperature and moisture conditions. The producing manufacturers can recycle used glass wool.

The second material is expanded polystyrene (EPS), usually obtained by evaporating the pentane added into polystyrene grains. This process allows the realization of a white, rigid, and closed-cell foam characterized by low thermal conductivity. Research activities demonstrated that the thermal conductivity of EPS is affected by moisture. They are usually commercialized as panels, easily handled and cut without losing performance. Specialized industries perform the recycling process of these kinds of materials.

Mineralized wood fibers are obtained by applying a mineralizing process to wood materials derived from poplar, fir (or other fast-growing plants), or residues of the sawmill industry. This process improves the fibers' resistance to fire, rodents, and insects. Portland cement is used as a binder to create panels that are quite heavy. These materials could be recycled even as concrete aggregates.

Finally, kenaf fibers are obtained from the *Hibiscus cannabinus*, a fast-growing plant able to reach 3.5 m of height in 2 years. Fibers are usually mixed with polyester and fire retardants. The absence of protein makes kenaf not attractive to rodents or insects. Concerning the environmental impacts, the kenaf fiber insulation board proved that if the plants are cultivated near the factory, and the disposal scheme of the exhaust panels consists of incineration with energy recovery, this material is less impacting than glass wool.

3. RESULTS AND DISCUSSION

Concerning the comparison between LEED and ITACA, it is noticeable that LEED gives more importance to material selection since a specific category (MR) has been assigned to this item (Table 1), and a maximum of 39 points depends on the insulation material properties (29 points in EA, 10 points in MR and 2 points in IEQ), while in ITACA they can reach up to 33.95% of the total score (29.40% in RC and 4.55% in IEQ). In addition, although in both certification methods, "Materials from renewable resources" and "Local materials" parameters are considered, LEED pays attention to using recycled materials as a strategy for reducing waste. This aspect is not considered in ITACA.

Both rating systems were applied to the examined building by analyzing the effects of different insulating materials on the partial and final scores. Tables 6 and 7 show the results considering the original categories before normalization. By observing the total scores, every building configuration obtained LEED certification (except the case with EPS) and Class C certification in ITACA. As a result, the impact of changing the insulating materials is very similar for both procedures, and the effects are about the same. In LEED, when EPS is installed as an insulating material, the building project does not reach enough points to obtain the certification, and, therefore, the proper choice of the insulating material is fundamental in achieving the certification.

As stated in the previous section, the insulating materials affect the results of two original LEED categories: "Energy and Atmosphere" and "Material and Resources", while in ITACA, only the "Resource Consumption" category is affected. Regarding LEED, in EA and MR categories, the use of EPS leads to a reduction of the partial score compared to the other cases. On the contrary, kenaf and mineralized wood fiber solutions have the highest scores in both categories. Regarding ITACA, in the RC area, EPS results as the worst choice as in LEED, while kenaf and wood fiber reach the highest partial score. These differences are mainly related to the different origin of the raw materials and the possibility of recycling or reusing them at the end of their life cycle. In addition, considering the material properties shown in Table 5 and the specific climate conditions of Catania, mineralized wood fiber is the most performing material in the energy categories because it is characterized by higher thermal conductivity and higher density related to thermal mass. As observed in Section 2.2, the proximity of materials production to the building construction site is relevant. For instance, kenaf, which can be found locally, allowed achieving a higher score compared to the other materials. Therefore, when selecting an insulating material, it is important to look at the environmental and energy performance they provide.

LEED	Glass wool	EPS	Mineralized wood fiber	Kenaf
Sustainable Sites	13	13	13	13
Water Efficiency	2	2	2	2
Energy and Atmosphere	17	16	20	18
Materials and Resources	4	3	6	7
Indoor environmental quality	5	4	4	4
Total	40	38	45	44
Rating level	**Certified**	**-**	**Certified**	**Certified**

Tab. 6. *Results for the LEED protocol.*

ITACA	Glass wool	EPS	Mineralized wood fiber	Kenaf
Site quality	3.00	3.00	3.00	3.00
Resource consumption	24.19	23.42	26.45	25.51
Environmental loads	5.50	5.50	5.50	5.50
Indoor environmental quality	5.48	5.48	5.48	5.48
Service quality	3.52	3.52	3.52	3.52
Total	41.69	40.92	43.95	43.01
Class	**C**	**C**	**C**	**C**

Tab. 7. *Results for the ITACA protocol.*

After the normalization process described in Asdrubali et al. [13] and the definition of the new five categories (Tab. 3), the results of the two rating systems were compared in Figure 3 and Figure 4. The total values refer to the maximum score achievable for each category, and it shows that LEED continues paying more attention to the “Materials” category (15 total points) compared to ITACA (10.4 total points). Differently, LEED pays less attention to the “Energy” category (30 total points) compared to ITACA (47.6 total points).

The only two areas affected by the materials change are “Materials” and “Energy”, similar to LEED. Focusing on the “Energy” category, the energy consumption of the building case study with glass wool was 30.73 kWh/m^2 calculated with DesignBuilder, while in the configurations characterized by the use of EPS, kenaf, and mineralized wood fiber, the energy demands were, respectively, 31.27, 31.15 and 30.75 kWh/m^2. In LEED, it results in different scores achieved by the insulation materials in the “Energy” category. Glass wool obtained about 63% of the maximum achievable category score influenced by changing the insulating material, the EPS obtained the lowest score (about 59%), while kenaf and mineralized wood fiber allow obtaining the highest score as design solution (about 67% and 74%, respectively). As described in the previous section, in ITACA, the impact on the “Energy” category is less accurate than LEED due to the energy assessment method adopted by modeling the real building and using a performance scale to assign points. Concerning “Materials” category in LEED, glass wool and EPS obtained, respectively, 40% and 30% of the maximum achievable category score influenced by changing the insulating material. Kenaf achieved 70% and wood fiber about 60%, resulting in the best performing in this category. However, these results show that, although kenaf and mineralized wood fiber can be considered sustainable and energy-efficient materials, they do not reach the maximum achievable category score influenced by changing the insulating material. Therefore, future research should consider alternative materials optimized for specific climate conditions.

Finally, in LEED, as can be seen in Figure 3, the renovation design project allowed to achieve about 57% in “Site”, about 17% in “Water”, and about 20% in “Indoor Environmental Quality” on the total achievable score for each category. Differently, in ITACA, the renovation design project obtained higher scores in “Site” and “Water” (more than 65% and 35% of the total achievable score, respectively), while in “Indoor Environmental Quality”, it was lower than 30% of the total score (Fig. 4). These

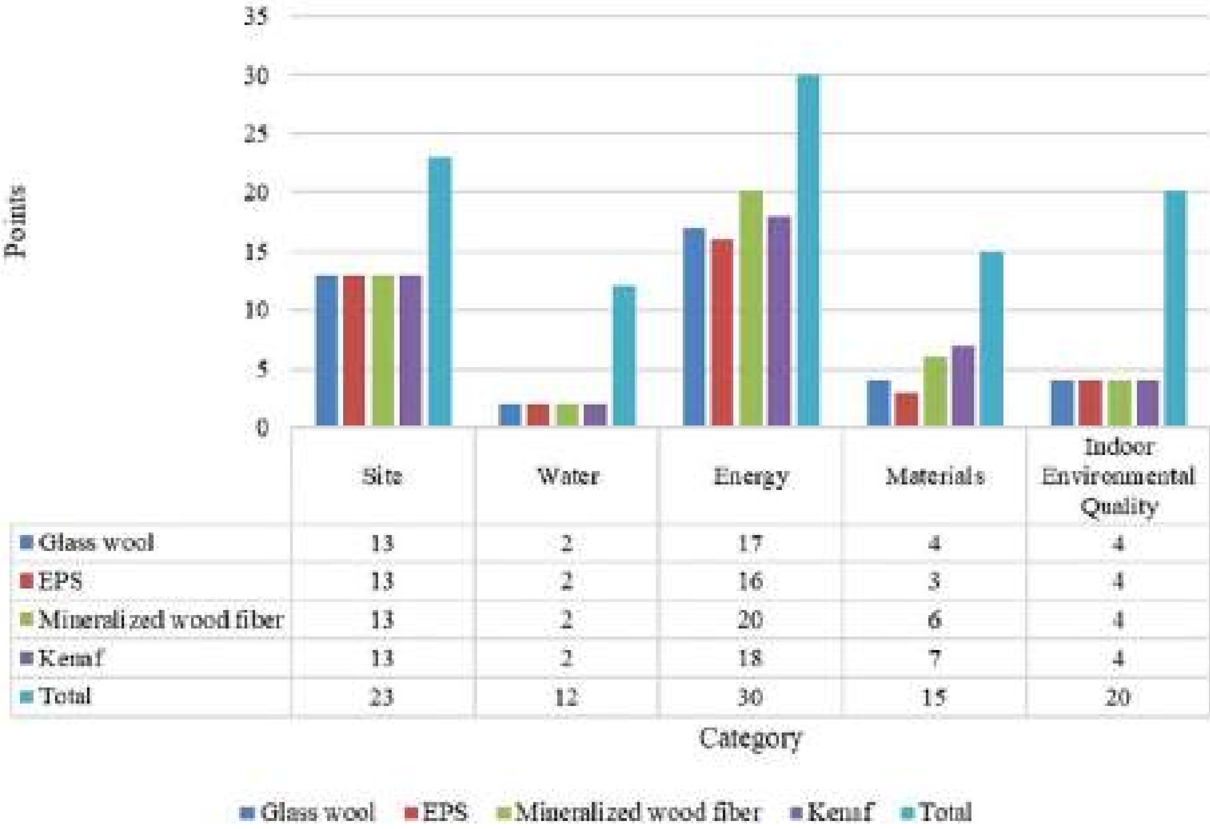

Fig. 3. *Comparison among the insulating materials in LEED.*

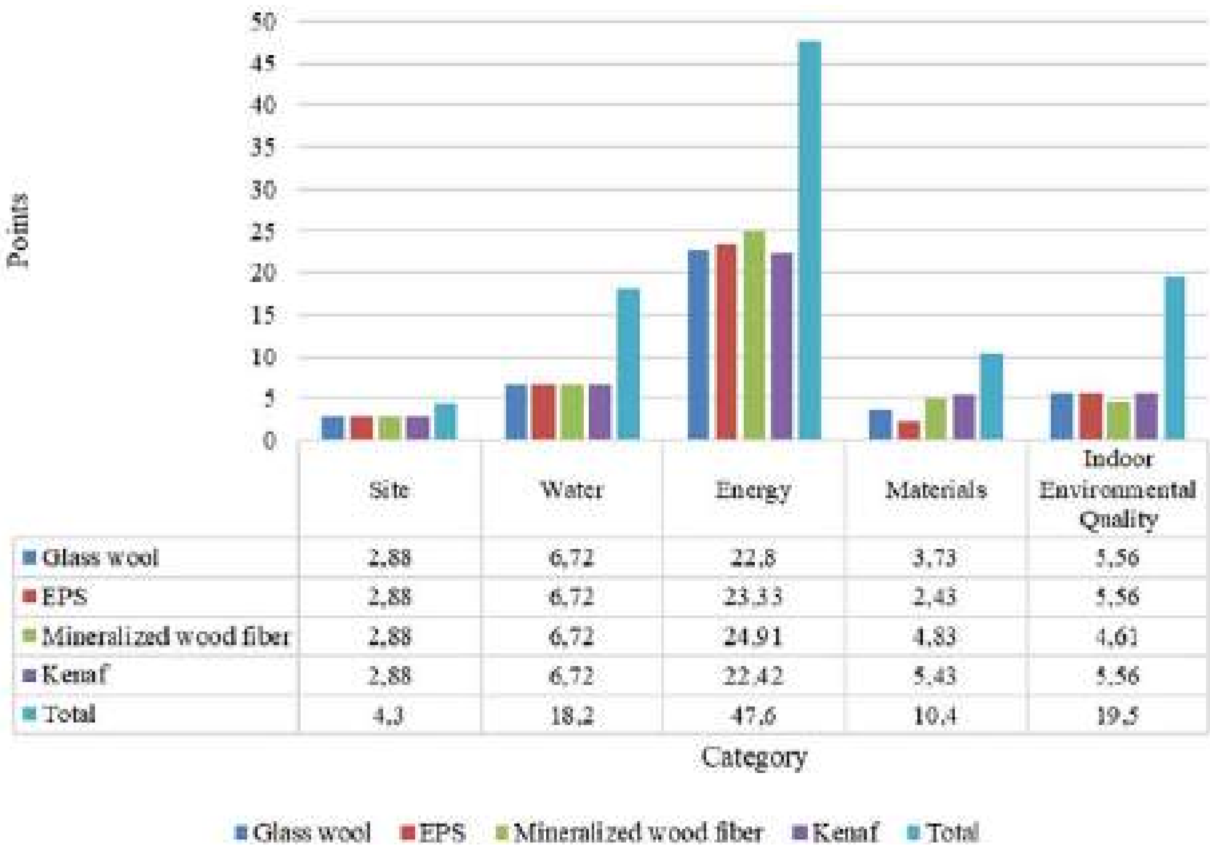

Fig. 4. *Comparison among the insulating materials in ITACA.*

results are not influenced by the change in insulating material and, therefore, their analysis is out of the scope of this research. However, it can be concluded that the building obtained many points in the categories related to the position of the building thanks to its closeness to both the urban city center and the mass transportation systems. At the same time, few points were obtained in the water and indoor quality categories because no intervention was included in the renovation project.

4. CONCLUSIONS

In this paper, a comparison between ITACA and LEED protocols applied to a renovation project in an Italian residential building was carried out. Five new categories were defined (Site, Water, Energy, Materials, and Indoor Environmental Quality) for comparing the two methods and their scores, according to previous research [13]. In addition, this research showed how and to what extent the insulating materials' characteristics can affect the two methods in the partial category and final scores. The sustainability rate of the building chosen as a case study was evaluated by simulating different configurations of the building envelope, characterized by thermal insulation made of glass wool, EPS, and two types of natural materials, mineralized wood fiber and kenaf. The following are the main results:

- after normalization, LEED pays more attention to the "Materials" category (15 total points) compared to ITACA (10.4 total points). Differently, LEED pays less attention to the "Energy" category (30 total points) compared to ITACA (47.6 total points);
- by observing the total scores, every building configuration obtained LEED certification (except for the case with EPS) and Class C certification in ITACA, demonstrating that the proper choice of the insulating material was fundamental in achieving the certification level desired;
- the mineralized wood fiber was the most performing material in the energy categories because it is characterized by higher thermal conductivity and higher density related to thermal mass. At the same time, kenaf, which can be found locally, allows for achieving a higher score in material categories thanks to the closeness of materials production to the building construction site;
- although kenaf and mineralized wood fiber can be considered sustainable materials, they do not reach the maximum achievable category score influenced by changing the insulating material because some of the points attributed to the "Materials" category directly depend on the building and the manufacturer locations and none of the materials proposed are manufactured close to the site.

Future research on this topic should consider other natural insulating materials (such as hemp, sheep wool, straw bale, etc.) that can allow for reaching the maximum scores attributed by the rating systems to the insulating materials. In addition, historic buildings represent most of the buildings located in the city center in which it is not possible to apply the thermal insulation layer on the exterior wall surface and, therefore, innovative materials should be explored to increase the thermal resistance of the envelope (such as aerogels, vacuum insulated panel, etc.).

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TESTING AND COMPARISON OF AN ACTIVE DRY WALL WITH PCM AGAINST A TRADITIONAL DRY WALL IN A RELEVANT OPERATIONAL ENVIRONMENT

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Abstract

As the building stock plays an essential role in meeting Europe's climate target, suitable strategies are necessary for the sector transition. This paper compares two dry-multi-layer walls characterized by different compositions: one applies heat reflective insulation with Phase Change Materials (PCM), while the second uses traditional glass wool batt. The experimental tests were conducted in a retrofitted building, the VELUXlab, a multi-testing laboratory located at Politecnico di Milano University (Italy), as one of the main outputs of the TEPORE project granted by the Lombardy Region. The temperatures and Heat Flux were measured through sensors between the inner and outer surfaces of the traditional wall (Dry Wall) and the false-wall with PCM (Active Dry Wall). The goal was to compare the two technologies evaluating the performance during daytime and nighttime in the winter season. Outcomes showed the advantages of the PCM application on space heating energy needs, revealing that their integration into the false-wall decreases the temperature by 1°C for a 30-40% thermal savings in the building envelope heat losses per week during cold seasons compared to the traditional wall. The study reveals that the PCM layer reduced the peak Heat Flux by 2.67 W/m^2 during the accumulation and release period.

Keywords

PCM, Dry construction technology, Energy efficiency, Thermal inertia, Sensors.

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1. INTRODUCTION

The European Parliament and the Council's request for highly efficient buildings [1] regard not only the near-zero annual balance between produced and absorbed energy (NZEB) [2] but also the reduction of life-cycle-related greenhouse gas emissions [3]. Indeed, almost 40% of in-home energy use is due to occupants' interaction with the building's systems [4, 5], generating an enormous amount of environmental impact [6, 7]. In this perspective, the adoption of Phase Changing Materials, mainly in lightweight technology [8], can be a suitable "carbon-effective" investment to refurbish existing buildings [9] or new constructions [10]. Even though the buying price of PCM is relevant, it has been observed that the payback cycle of the system is efficient thanks to the cost of energy saved [11] by lowering the cooling and heating demand. In active systems, the PCM is a possible heating peak load shifting strategy for buildings to achieve indoor thermal comfort, especially for applications to existing buildings to improve the current installation's performance [12]. On the one hand, auxiliary studies on dynamic energy simulation show that construction solutions with PCMs can cut consumption by flattening the indoor temperature fluctuations and reducing/shifting the load peak [11] due to the heating store capacity of the material (artificial inertia). On the other hand, the monitoring campaign on indoor environmental quality metrics and energy consumption of a building designed with PCM and installed in the second story of the west unit [13] shows that the installation of PCM had a positive effect on thermal comfort, reducing the estimated annual overheating hours from about 400 to 200 and that has a significant impact on the building's energy consumption.

Some other research [14] demonstrated that a suitable storage system capable of accommodating the thermal loads arising within the room during the daytime, a 5 cm layer of microencapsulated PCM (25% by weight of the ceiling material) and gypsum in a ceiling panel are sufficient to maintain a comfortable room temperature in standard office buildings [15]. The addition of a PCM layer to building walls [16] shows that: (i) the PCM-integrated walls are advantageous mostly in moderate climates and when the daily temperature swings should be favorable to permit free ambient cooling/heating; (ii) the transition temperature of the PCM should be optimized to enhance the utilization of the PCM; (iii) the location of the PCM in the wall should be tweaked so that the layer can interact with both the exterior as well as the interior environments. A further study [17] highlighted that incorporating PCMs in buildings' walls, floors, and ceilings can significantly release load management. Indeed, PCM can offer a higher storage capacity [18] associated with the latent heat of the phase change, accumulating and discharging heat and cold on-demand, and controlling humidity in various applications. Additionally, different parameters may influence the performance of PCM, as the location of the PCM layer embedded in walls and the environmental conditions [19] affect the thermal proprieties, as the absorption and release of latent heat can radically change. The study reports that PCM with a transition temperature of 22-24°C, located in the middle of the wall, reduces the annual heat gain by 3.5%-47.2% and the annual heat loss by -2.8% and 8.3%, depending on the location considered in this reference study using USA climate [16].

Although the literature shows many studies related to the PCM effectiveness measurement, only some studies compare their efficiency by analyzing data from case studies instead of digital/theoretical models. Therefore, the need to further investigate the PCM application with a work aiming to compare the behavior of two real false-wall, one with PCM, to assess their inertial capacity in heating mode. The intention is to support the ecological transition to a more sustainable – and ethical – approach to buildings by estimating the amount of energy savings thanks to the combined use of sensors and a thermographic survey. This double method of analysis looks at meliorating not only the quality of life and integrity of buildings but also that of individuals according to climatic zones and comfort requirements.

Accordingly, the obtained results for the winter season could be examined and verified in further development for the summer season, where the artificial inertia capacity of Phase Changing Materials allows for flattening the temperature peak around noon and releasing stored heating during the night.

2. METHODS

The present paper aims to compare two types of portions of multi-layer technology false-walls – the first is called Active Dry Wall with a layer of phase change materials (PCMs) between the gypsum boards, and the second is a traditional Dry Wall [20]. They were installed as two portions of counter wall in VELUXlab, a Politecnico di Milano test building. This work is part of the TEPORE project, a research project supported by the Lombardy region (Italy) that evaluates the application of innovative envelope technology based on the heat sink effect [21] in efficient and intelligent buildings under heating through a sensor-based upgrade approach [22]. The selected technologies were chosen because of their market diffusion as a standard dry wall solution to compare with an efficient PCM layer composition among materials furnished by the project partners. The comparison between various building components and products is carried out through their on-field performance by checking, monitoring, analyzing, and optimizing the energy consumption and comfort in heating mode.

Several sensors were installed between the false-walls to detect the surface temperature and heat flow. Realizing two sensor walls with different stratigraphy allows for verifying their efficiency by an on-site survey of a data series derived in a digital environment. The smart control technique is applied to enhance and monitor their performance and make them cost-effective [12] from the sustainable design perspective, i.e., BIM 6D [23].

The research evaluates PCM's energy performance for 69 days within a test facility building to observe the winter seasons' behavior compared to traditional dry wall technological solutions [14, 21]. The progress ensured by the data collected is crucial to understanding the material's behavior in different climate conditions (rainy, cloudy, and clear sky), the humidity of the environment and the radiation level as a parameter of influence for the artificial inertia performance. The survey was taken from 24th November 2018 until 1st February 2019. The results are reported both in a medium-term perspective (Section 3.3. *Weekly Analysis*: 24th–30th November), with a daily focus (Section 3.2. *Daily Analysis*) and on-the-spot comparison, as expected behavior of the technology during the winter period (Section 3.4. *Weekly Comparison of Active Dry Wall and Traditional Dry Wall*). Parallelly, on the 6th and 12th of November 2018, a thermographic survey (Section 3.1. *Thermographic Survey*) analyzed the surface temperature of the wall to check and compare results with analytical data from sensors (Section 3.5. *Temperature Section Analysis*).

2.1. COMPONENTS FEATURES

The energy performances of the two dry wall technologies (Active Dry Wall and Dry Wall) are compared using the monitoring data collected by sensors. In particular, sensors are inserted into different layers of the two false-walls installed on the existing building envelope, as described in Section 2.2 Experimental setup. The stratigraphies of the two false-walls are:

- Active Dry Wall: plasterboard, PCM sachets, plasterboard, reflective honeycomb thermal insulation, air cavity, thermal reflective insulation;
- Dry Wall: plasterboard, air cavity, plasterboard, glass wool insulation, air cavity, thermal reflective insulation.

The main thermal properties of the wall materials are reported in Table 1.

Item	Width x Height (mm)	Thickness (mm)	Density (kg/m³)	Specific Heat Capacity (J/kgK)	Thermal conductivity (W/mK)	Quantity
Laths for fixing Multi-Reflective Insulation	40 x 2,000	15	-	-	-	1 m²
Metal frame	C,U 40 x 2,000	75	-	-	-	7.4 m
Gypsum board	1,200 x 2,500	12.5	680	1,000	0.21	10 m²
Thin Multi-Reflective Insulation	1,220 x 2,000	-	20	1,450	0.04	5 m²
Honeycomb insulation	550 x 2,000	100	9	2,300	0.033	2 m²
Glass wool	550 x 2,000	75	21	1,030	0.33	2 m²
PCM	124 x 122	12.5	14,000	Solid state 5,000 Liquid state 2,000	0.93 0.75	6 sachets

Tab. 1. *Material items referred to Dry Wall and Active Dry Wall installed on the south side of the east wing of VELUXlab. Characteristics of Thermal Capacity and Thermal Conductivity of PCM in the solid and the liquid state.*

Specifically, thermo-reflective insulation is multi-reflective thin insulation based on sheep wool, airtight and watertight. It is positioned to detach the two false-walls from the effect of the external closure behind them. In particular, it preserves results from direct radiation affecting the west wall during the afternoon and avoids heat loss from inside to outside during the night. The honeycomb insulation ensures winter and summer thermal insulation, acoustic insulation, and airtightness of buildings. The glass wool is used for thermo-acoustic insulation of walls, false-walls and false ceilings made with the dry system. Finally, the PCM used is a commercial solution (ClimSel C21©) in salt hydrate-based material in aluminum packets. Its main components are sodium sulphate, water, and additives. The starting melting temperature range is between 21°C (solid) and 26°C (liquid); the latent heat of fusion is 134 kJ/kg for a liquid density of 1.4 kg/l.

The internal false-walls were positioned in contact with the existing vertical closure, detaching the two walls by inserting thin reflective insulation using a galvanized lightweight metal frame with C studs and a U transom to contain the insulation. Different insulation layers characterize the systems because of their diverse behavior: the thermo-reflective insulation has no inertial performance, provided by the PCM sachets, while the traditional Dry Wall provides it through the glass wool. The two systems are selected because they are two conventional dry wall layers available on the market with comparable thermal transmittance.

The two walls are mainly differentiated by the presence of a layer of Phase-Change Material in the Active Dry Wall between two layers of plasterboard, whereas the traditional Dry Wall has an air cavity. The hydrate salt materials accumulate significant amounts of heat while maintaining a constant temperature during the transition phase (between 21°C and 26°C for the PCM material adopted: sodium sulphate, $Na_2 SO_4 \cdot 10H_2O$).

The two walls' comparative performance analysis is based on the PCM characteristic to exploit the cycles of heat release and heat absorption, allowing the regulation of the thermal condition of indoor environments during the heating time. The material allows heat flow while maintaining the same physical state. The material allows heat flow while maintaining the same physical state. The material starts its phase transition during its melting temperature, maintaining a constant temperature until the transition is complete when the heating flux restarts. The heating flux can be considered positive during the day when PCM stores heating by absorbing it from external radiation and negative during the night when the heating absorbed is released. The capability to store thermal energy related to phase transitions, allowing a temporary accumulation of thermal energy at a higher temperature and its release at a lower [21], can be described as "artificial inertia" [24]. According to the comfort temperature setup, the melting temperature of PCM is 21°C, although the inner temperature and the PCM surface temperature can be higher because of their location. The salt-hydrate superficial temperature can come up to 26°C in the winter because they are affected by direct sun radiation from the south window. The temperature can continue to increase once the transition to the liquid state is complete.

The comparative analysis of the performance [25] of the two walls in the facility building of VELUXlab, focuses primarily on the monitoring process through "sensing". The sensorization of walls is functional to collect data through the surface temperature and heat flow of the two technologies in the inner and outermost layers. As the building's nature is an office, comfort temperature is settled at the 20-26°C range and a working schedule of 8:00–18:00. During the winter season, the outside temperature float between -5°C and 10°C, with 2°C–7°C of average temperature in December.

2.2. EXPERIMENTAL SETUP

The case study of this research, which is part of the TEPORE project in collaboration with Smart Living – an initiative to investigate technologies and products application in home buildings – is VELUXlab, a multi-test building of the Politecnico di Milano at Bovisa Campus neighborhood in the northern part of the city (Fig. 1). The false-wall was installed against a portion of the west wall of the east wing of the VELUXlab, near three roof windows that allow light to enter and break down against the new construction (Fig. 2).

The data survey took place from 24th November 2018 until 1st February 2019 with a time step of 15 minutes. It was functional to test the proper functioning of these sensors and design the system of graphic representation

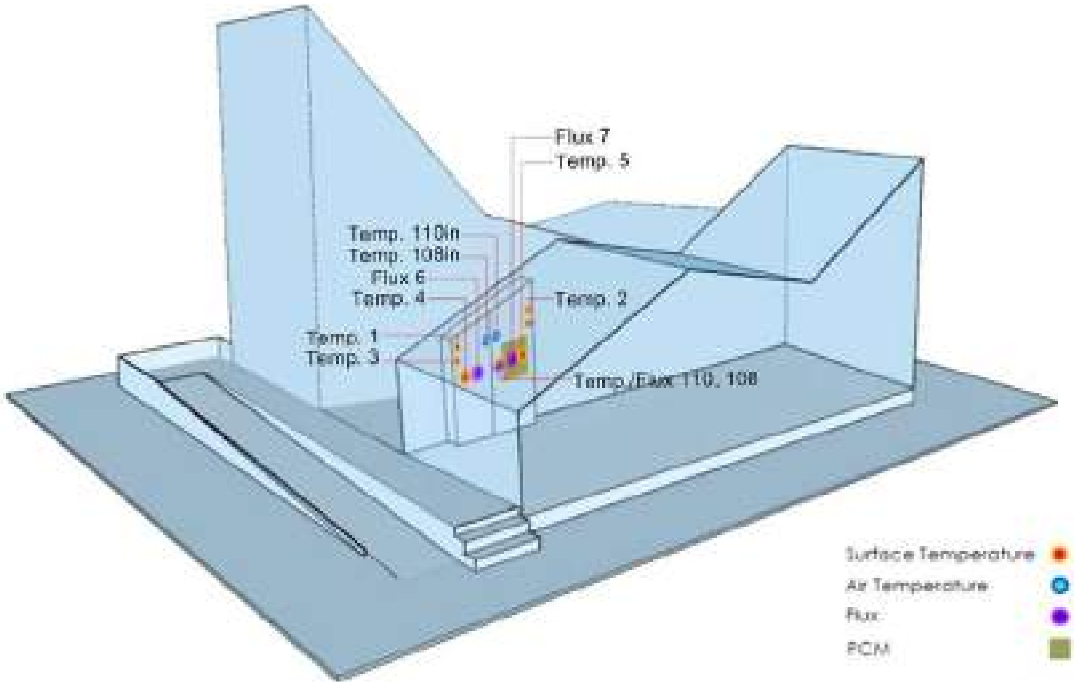


Fig. 1. *The 3D view of the east wing monitoring system: the Dry Wall, on the left side, and the Active Dry Wall, on the right one, installed on the south side of the east wing of VELUXlab.*

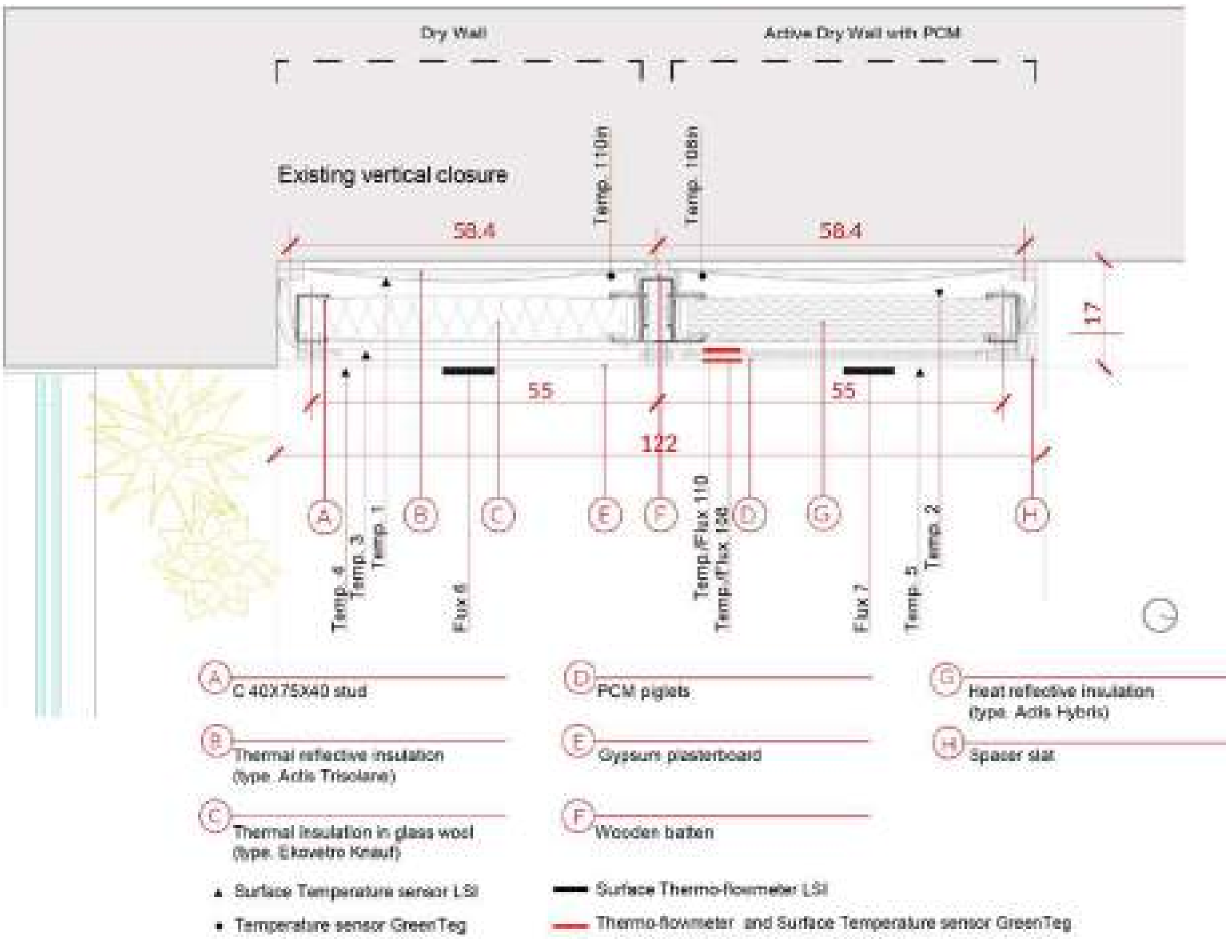


Fig. 2. *The horizontal section of the Dry Wall on the left side and the Active Dry Wall on the right one, installed on the south side of the east wing of VELUXlab, highlighting the sensor's location and the technology layers' composition. The two false-walls are detached from the existing vertical closure thanks to a vertical insulation layer (B) and the wooden batten (F).*

of the data collected. As described in Figure 2, the fully sensorized wall was equipped with the following:

- five surface temperatures and two flow sensors: LSI-LASTEM type (Temp.1_Dry Wall, Temp.2_PCM, Temp.3_Dry Wall, Temp.4_Dry Wall, Temp.5_PCM, Flux6_Dry Wall, Flux7_PCM).
  [The LSI-LASTEM features for Temperature (T) and Heat Flux (HF) are, respectively: Operational temperature range (°C), -50 to +70 (T), -30 to +70 (HF); Accuracy measurement, +/-0.1°C (T), +/-5 kW/m^2 (HF); Resolution sensors, 0.01°C (T)].
- two aerial temperatures and two flow and surface temperature sensors: GreenTEG type (Temp.110_Dry Wall, Flux.110_PCM, Temp.108_Dry Wall, Flux108_PCM, Temp.108int_PCM, Temp.110int_PCM).
  [The GreenTEG features for combined Temperature and Heat Flux are: Operational temperature range (°C), -40 to +80; Accuracy measurement, +/-0.1°C (T), +/-3 % (HF); Resolution sensors, 0.01°C (T), 0.09 W/m^2 (HF)].

The technology of materials and layers is defined as "invisible" because of the high performance achieved in small thicknesses. The use of multi-reflective materials and the high thermal capacity of PCM turn the building into "active" and even more "reactive" to external climatic stimuli in a shorter time. The experiment is conducted by creating two new false-wall portions instead of modifying the existing vertical closure. Sensors installed in the smart dry walls have constantly monitored the real performance of the envelope-plant-interior environment system (indoor comfort). The montage was carried out over the two half-days on the 10th and 11th of July 2018 (Tab. 2).

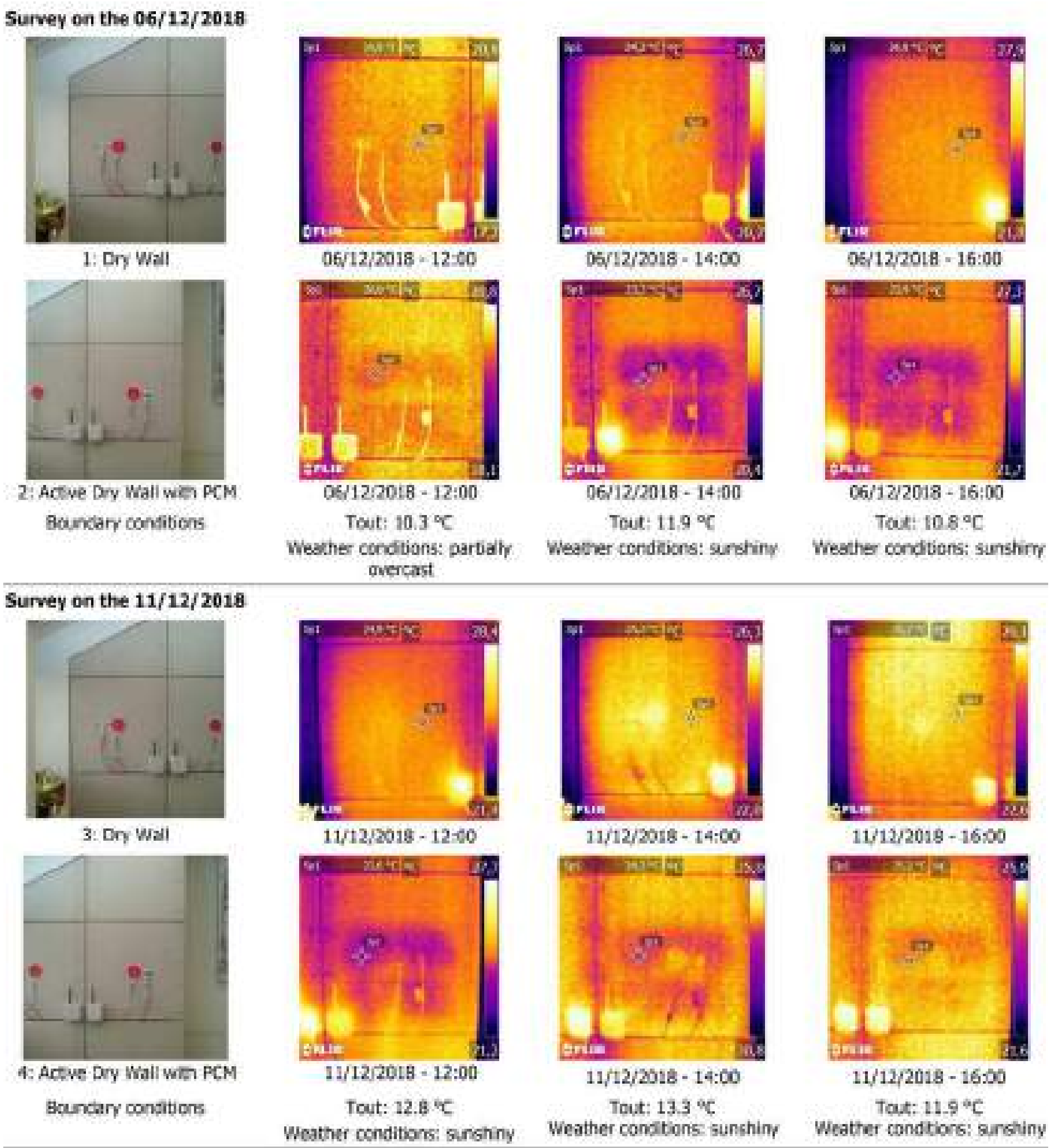
Tab. 2. *The installation phases with eight steps of the Dry Wall on the left flank and the Active Dry Wall on the right one, installed on the south side of the east wing of VELUXlab.*

The two Dry Walls are identically sensorized (Tab. 2 phases 6, 7 and 8) to collect and retrieve data. Data collected are analyzed from generic data (thermographic survey) to specific (sensors analytical values) and from the instantaneous moment to weekly behavior to extend the results to the whole winter season. This approach follows incremental knowledge progress by understanding the global effect of the PCM compared to a simple dry wall at first with lower precision data coming from the thermographic survey and then validating the results by quantifying the effective benefits of heating flux savings by the analytical sensor data collection.

3. RESULTS

3.1. THERMOGRAPHIC SURVEY

A thermographic survey campaign was conducted with the support of a FLIR T400 thermal camera. This survey aims to verify the thermal operation of the two technologies by observing the radiation emitted in the infrared range of the electromagnetic spectrum. The external temperature and weather conditions are collected by the closest weather station located in the northern area of Milan because of the influence of direct radiation and environmental temperature on the results.



Tab. 3. *The thermographic survey performed from 06/12/2018 to 11/12/2018 on the Dry Wall on the left flank and the Active Dry Wall on the right one, installed on the south side of the east wing of VELUXlab.*

The analysis was carried out simultaneously in three hours steps (12:00, 14:00 and 16:00), selecting days with similar weather conditions (sunshiny) to avoid the influence of environmental and climatic conditions of the place under analysis. The two chosen days are the 6th and the 11th of December (Tab. 3).

The results show a constant difference between the surface temperature of the Dry Wall insulation and the Active Dry Wall for both surveys: around 1°C higher for the glass wool insulation due to PCM's most significant heat absorption by its phase change. In the first survey (Tab. 3) on 6th December, the surface temperatures of the PCM and the glass wool insulation are similar (19.9°C and 20°C, respectively) because there is no direct sunlight affecting the wall (partially overcast weather conditions). In the second survey on 11th December, the initial delta at noon is higher (1.3°C, resulting from 24.9°C of the Dry Wall and 23.6°C of the Active Dry Wall) because of the radiation affecting the false-wall throughout the morning.

The higher reduction of the outside temperature from 13.3°C to 11.9°C accelerates the PCM inertial capacity reversion. It released the heat accumulated to the internal environment, having a similar surface temperature to the Dry Wall (0.5°C of the delta at 16:00 on 11th December instead of 1°C on 6th December).

3.2. DAILY ANALYSIS

The proposed analysis realized through fully sensorized walls aims to estimate their energy performances. The heat flow graphs measured on the Dry Wall (sensor Flux6_Dry Wall in Fig. 3a) and the Active Dry Wall with PCM (sensor Flux7_PCM in Fig. 3b) highlight the effect of both walls from the radiation metrics (the blue bar in the charts) as general behavior, with positive values when the sun is present. As a result of the solar radiation intensity peak (6.53 W/m^2 at noon), the surface temperature of the two walls (Temp.4_Dry Wall and Temp.5_PCM) increases together with the inner temperature, reaching the same temperature around 11:00 (21.22°C and 21.24°C respectively for the Dry Wall and the Active Dry Wall).

Instead, the different inertial capacity produces an effect on solar radiation: the Dry Wall closes the gap by approaching the values between the inner air temperature and its surface temperature after the solar radiation intensity peak (0.17°C at 15:00, 0.8% of the indoor temperature), while the Active Dry Wall saves 0.88°C, that is 4.1% of the inner temperature. This delta is constantly maintained during the whole day (0.76°C as the daily average value, around 3.8%), while the Dry Wall release more energy during the night, having at midnight a delta of 1.68°C (7.5% of the inner temperature), compared to 0.62°C (only 2.7% of losses) of the Active Dry Wall.

The difference between the delta daily average value for PCM (1.28°C, 0.6% minor than the inner temperature) and Dry Wall (0.76°C, 3.5% lesser than the internal temperature) is 0.52°C. Therefore, it is 2.5 times higher than the traditional solution, which reflects the superior attenuation capacity of the artificial inertia of the PCM material compared to the traditional one and results in a higher surface temperature during the night, levelling the peaks.

The Heat Flux analysis shows some delays between the two solutions: the accumulation period of Dry Wall starts at 6:00 (Fig. 3a), two hours before the PCM (8:00 in Fig. 3b), and finishes at 16:30, half an hour before the active Dry Wall. The peaks also confirmed the delay: PCM peak is 13.7 W/m^2 at 14:00, while the dry false-wall is 11.1 W/m^2 at 13:00 with a delta of 2.6 W/m^2 between the two maximum values. Comparing the area under the curve, the PCM Heat Flux is 20-30% higher in the accumulation period because of the delta of peaks, despite 1.5 hours less of accumulation. The trend is again confirmed during the night: the negative peak is 1.9 W/m^2 for the dry false-wall at 19:00, while the Active Dry Wall is -4.4 W/m^2 at 1:00. The discharger phase (highlighted in blue) is 2.3 times higher for the PCM due to its (artificial) inertial capacity. The global heating energy transfer for a single day (30th December) results in a reduction of 40%.

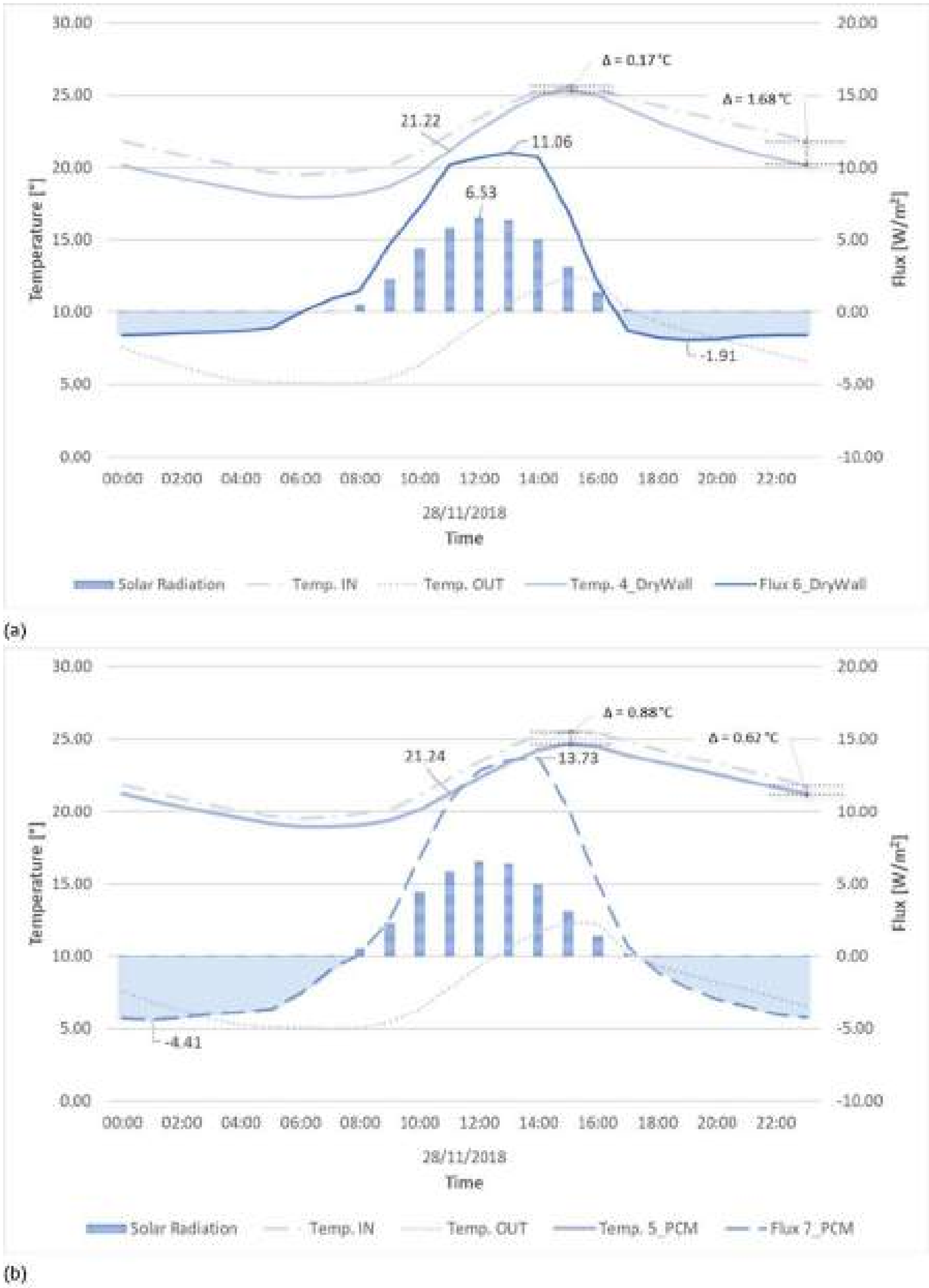


Fig. 3. *The Daily Analysis (28/11/2018) realized. (a) The Heat Flux (sensor Flux6_Dry wall) and the Internal Surface Temperature (sensor Temp.4_Dry wall) of the Dry Wall – related to Inner and Outer Temperature (Temp.IN/Temp.OUT) and the Solar Radiation. The surface temperature (Temp.4_Dry wall) is close to the Inner Temperature peak at 15:00, while the discharger phase is relatively small compared to the accumulation period. (b) The Heat Flux (sensor Flux7_PCM) and Internal Surface Temperature (sensor Temp.4_PCM) of the Active Dry Wall with PCM – related to the Inner and Outer Temperature (Temp.IN/Temp.OUT) and the Solar Radiation. The surface temperature (Temp. 5_PCM) is constantly 0.9°C lower than the Temp.IN, while the accumulation and the discharger phases are similar in embodied energy thanks to the heat sink effect of PCM (artificial inertia).*

3.3. WEEKLY ANALYSIS

The weekly analysis (Fig. 4) shows a close to zero Heat Flux exchange for November 24th and 25th because the office was not populated, with closed shadings preventing radiation from acting on the false-walls and a set-point for the heating system of 17°C minimum. From Monday 26th to Friday 30th, the general path described is confirmed, showing a flux delay of 1 hour, a higher accumulation capacity of 20-30% and a similar gap of 2.7 W/m^2 in the negative peak. The accumulation peak shrinks when the radiation is lower: both are around 2 W/m^2 lower on the 29th and 30th, while the heating release is unrelated to the radiation path.

Besides, specific analysis for the portion of the wall with PCM (Fig. 5) compares the Heat Fluxes measured on the inner face of the plasterboard before the PCM (sensor Flux110_PCM) and on the exposed surface in the room after the PCM (sensor Flux7_PCM). The two surfaces have opposite Heat Flux curves due to the PCM heat shield effect. In the morning, salt and paraffin collect heat from the external surface – thanks to the direct sunlight – oppositely, the PCM releases the stored heat to the inner space during the night. The honeycomb reflecting insulation avoids heat loss to the external side, directing it to the inner side and coming to zero flux.

The global accumulation flux is 4.5 times larger than the discharger peaks; the proportion between the sunlight hours (13.73 W/m^2 on the 28th) and the night release (-4.31 W/m^2) is also confirmed on the 27th, as highlighted in the graph (Figure 5). On this day, the delta between accumulation (+15.31 W/m^2) and the release peak (-5.88 W/m^2) is also higher (21.19 W/m^2 on the 27th; 19.44 W/m^2 on the 28th) because of the high level of the outer temperature (14.5°C on 27th and 12.3°C on 28th).

Similarly, the releasing period shows the same path: the discharger delta at night (around 1:00) is about 4.71 W/m^2 on the 27th and 4.5 W/m^2 on the 28th, respectively,

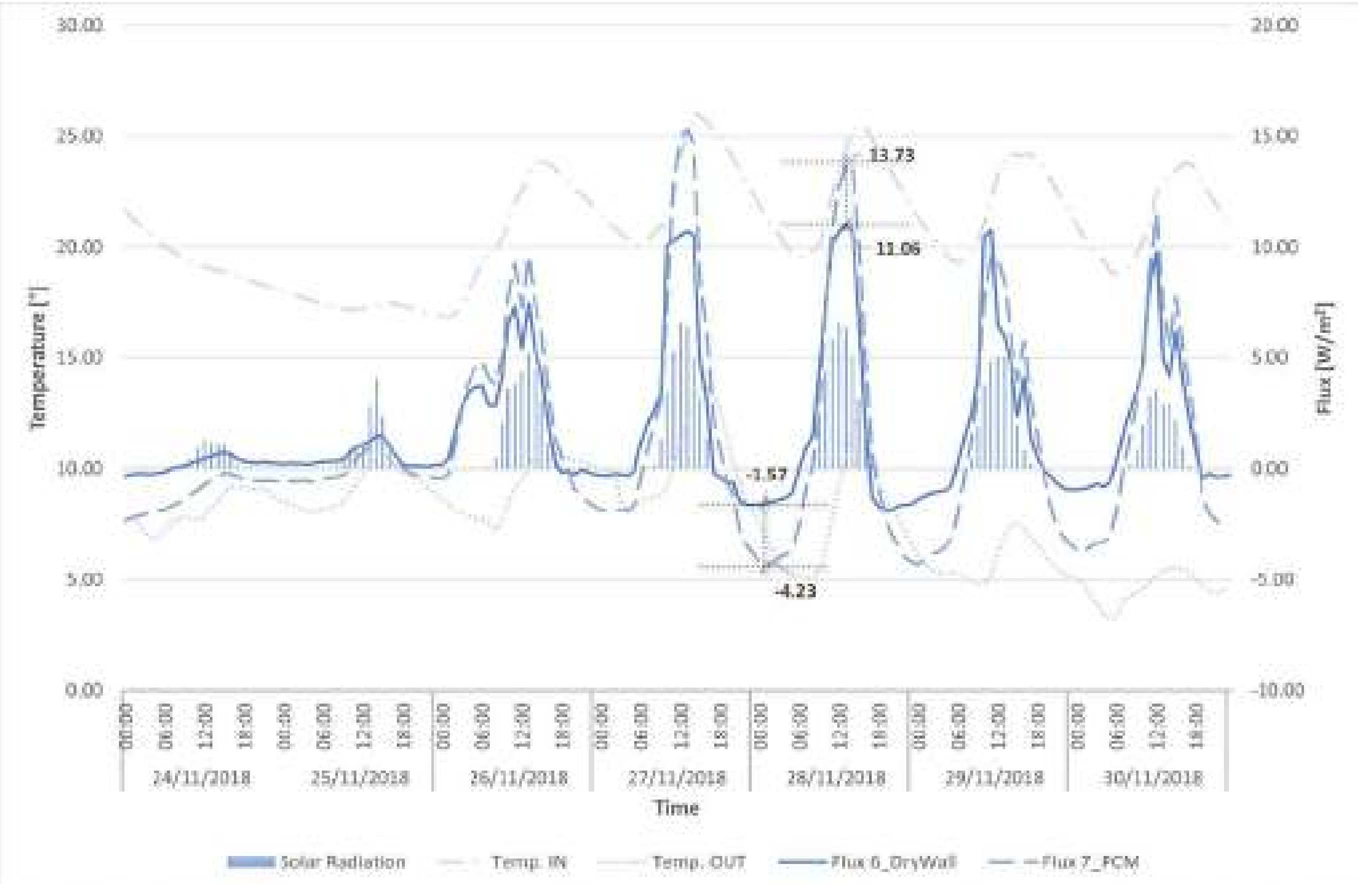


Fig. 4. *The image shows the Heat Flux path during the week for the Dry Wall (Flux6_Dry Wall) and the Active Dry Wall with PCM (Flux7_PCM). The Active Dry Wall heat flux follows the Radiation flow during the day: the accumulation peak is lower, and the radiation during cloudy days on 29/11/2018 and 30/11/2018.*

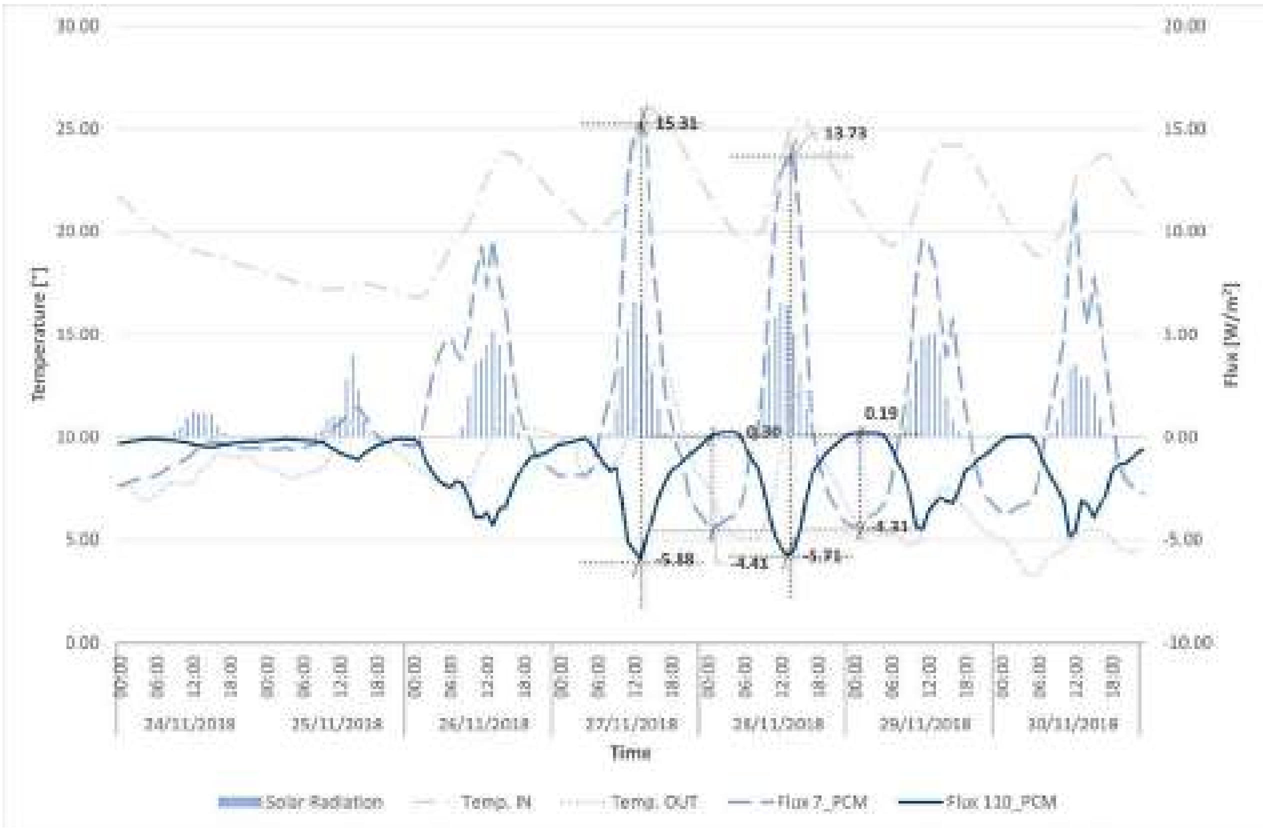


Fig. 5. *The comparison of Heat Flux measured on the plasterboard behind the PCM (sensor Flux110_PCM) and the external surface of the Active Dry Wall (sensor Flux7_PCM). Fluxes are inverted during the day and the night: the deep blue line displays the PCM absorption during the day and its release during the night toward zero. The dotted line displays how the false-wall surface releases heat during the night.*

4.5 and 4.32 times the accumulation. Regarding the absolute value, the absorption peak (15.31 W/m^2 and 13.73 W/m^2) and releasing peak (-5.88 W/m^2 and -5.71 W/m^2) proportion is 2.4 on both days, 27th and 28th, respectively.

3.4. WEEKLY COMPARISON OF ACTIVE DRY WALL AND TRADITIONAL DRY WALL

The overlapping of the two graphs previously analyzed (Figs. 4, 5) supports the parallelism of the two opaque envelope technology thermal hour-by-hour behavior per week.

The comparison (Fig. 6) between the flux and temperature measured on the Dry Wall (Flux6_Dry Wall and Temp.4_Dry Wall) and the Active Dry Wall with PCM (Flux7_PCM and Temp.4_PCM) highlights that the Active Dry Wall works as a “solar collector with artificial inertia”. The Active Dry Wall with PCM has a similar surface temperature during the sun hour, while the Heat Flux is considerably higher, with a zenith around 14:00 when the direct sunlight stops affecting the wall. From this moment, there is a reversion in the Heat Flux, having a negative peak at midnight: the heat stored during the day is released during the night, allowing better indoor comfort for the users, as shown by the 1°C higher surface temperature for PCM false-wall.

Location, inner and outer temperature, relative humidity, and radiation are the same for both technologies, and the results clearly show the reverse behavior of the two false-walls: the Dry Wall with traditional insulation causes higher temperature variation on the external surface (Temp.4_Dry Wall) with lower flux variation. At the same time, the Active Dry Wall with PCM has a stable surface temperature (Temp.4_PCM) delta of 1°C from the internal temperature by a more extensive range in positive and negative heating flux (20–30%). However, the weekly global heating energy transfer of Active Dry Wall saves 29% thanks to artificial inertial technology.

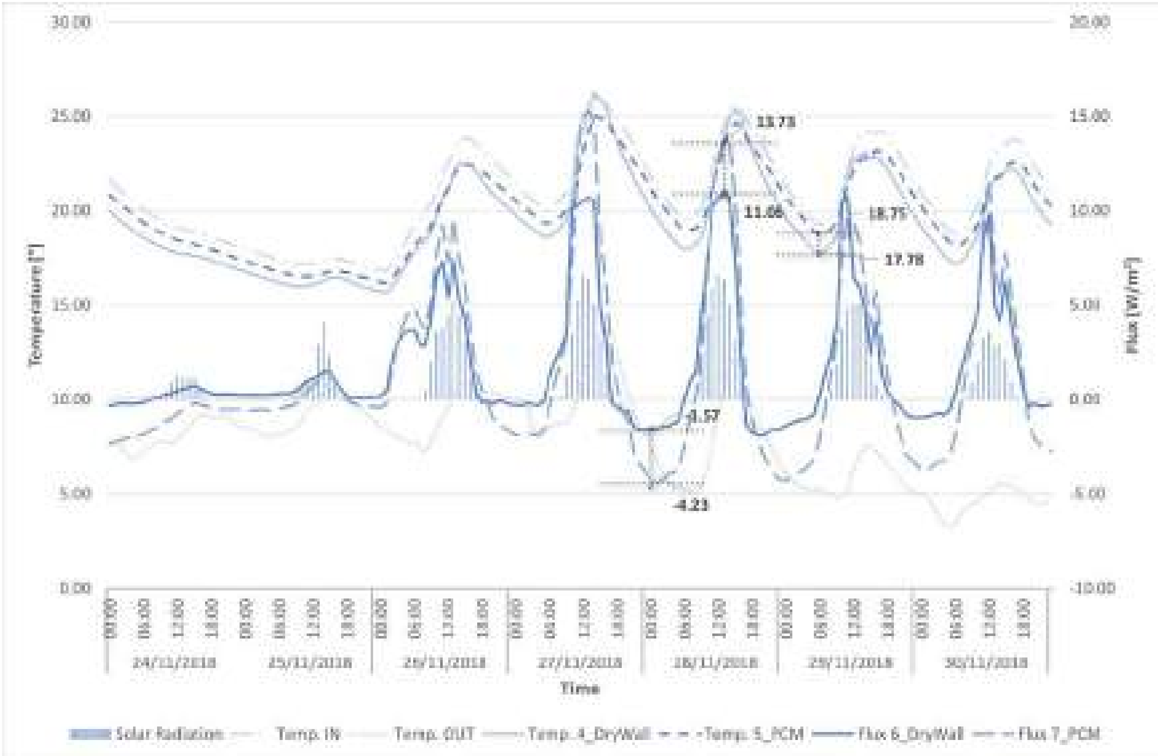


Fig. 6. *The comparison of the Heat Flow (sensor Flux6_Dry Wall and Flux7_PCM) and Internal Surface Temperature (sensor Temp.4_ Dry Wall and Temp.4_PCM) of the Dry Wall and the Active Dry Wall installed on the south side of the east wing of VELUXlab. The weekly sum of the accumulation and the release of heating results is 18.1 W/m² lower for the Active Dry Wall one.*

3.5. TEMPERATURE SECTION ANALYSIS

The weekly comparison of the two technologies analyses the temperature trends section (Fig. 7) at every layer of both technologies during the day (black dot line) and night (red dot line). The comparison is on the level recorded at 14:00 on 26/11/2018 and 2:00 on 28/11/2018.

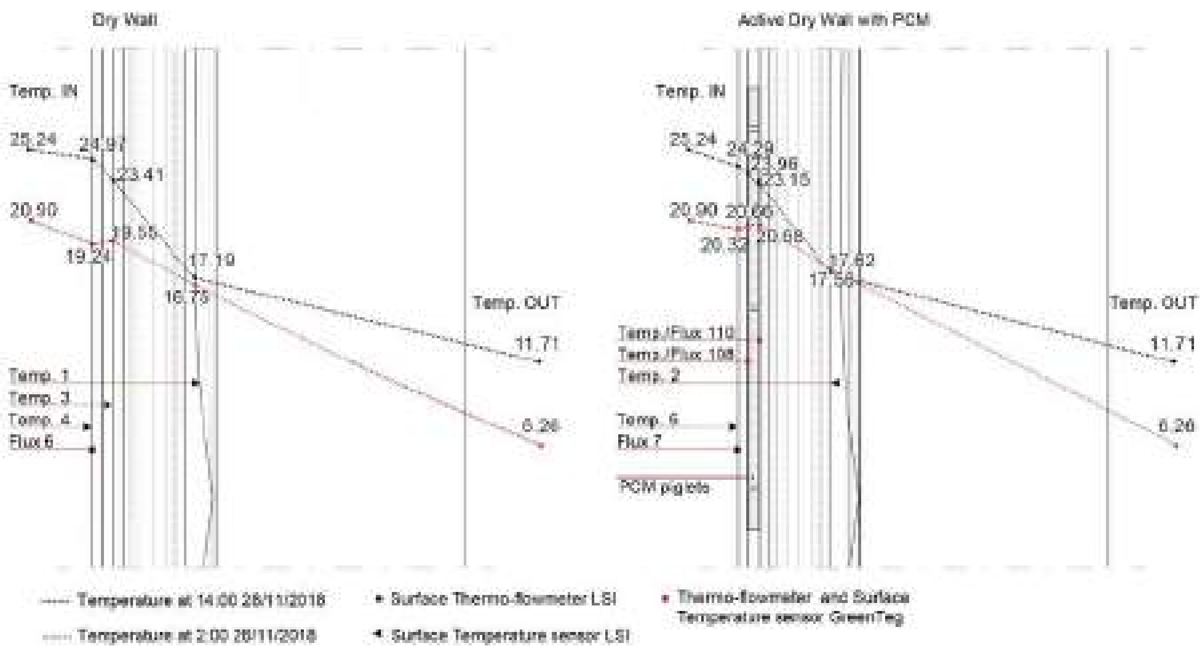


Fig. 7. *The temperature trends of the walls installed on the south side of the east wing of VELUXlab. The comparison of the measurements was recorded at 14:00 (black dot line) and 2:00 (red dot line) on 28/11/2018 on the wall with the Dry false-wall (sensors Temp.1_Dry Wall, Temp.3_Dry Wall, Temp.4_Dry Wall) and the Active Dry Wall with PCM addition (sensors Temp.110_PCM, Temp.108_PCM, Temp.2_PCM, Temp.4_PCM.*

On the left side, the surface temperature of the dry wall is higher (+0.7°C) as well the one measured on the second plasterboard (0.26°C); on the reverse, during the night, the PCM shows a 20.66°C temperature, 1.11°C more than the dry wall (19.55°C). Its artificial inertia causes the temperature turnaround, having a higher temperature on the thermo-reflective layer at night (17.62°C against 16.75°C).

4. CONCLUSIONS

The theme addressed in this paper emphasizes the importance of promoting research, development, innovation, and the "home system" for achieving the EPBD Directive 2010/31/EU request for NZEB buildings. The research was developed within the TEPORE project, performed at Velux Lab, a Politecnico di Milano test building, analyzing PCM's energy performance and efficiency concerning traditional Dry Wall technologies for heating sink effect. The sensorization of the various envelope layers has shown how Active Dry Walls with PCM materials inside can accumulate considerable heat during winter sunlight hours and release this heat at night. This process leads to a weekly global heating energy transfer saving of 29%, resulting in an energy balance cost reduction. The thermal mitigation of the heating peak around noon is 2.6 W/m^2 lower for the PCM material due to the 20–30% higher heating flux during the accumulation period, while the thermal peak delay is one hour later than the Dry Wall.

Symmetrically, the discharger peak is 4.4 W/m^2: 2.3 times higher for PCM at night. Furthermore, the surface temperature analysis shows a reduction of 1°C for PCM Active Dry Wall compared to a glass wool insulation Dry Wall due to the salt heating absorption by its phase change, resulting in a higher environmental comfort for users.

Subsequently, the results open a window to support the meliorating of life and integrity of buildings and individuals according to climatic zones and comfort requirements. Thanks to the advantages of adding artificial inertia to an existing envelope, the performance can be improved by shifting the heating peak load and flattening the indoor temperature. The meliorating of the quality of a space concurs with the ecological transition creating a context where also individuals increase their quality of life, under the possibility of also reducing energy costs. However, some implications can be related to the summer season, which this study did not verify, even though artificial inertia could act as heating storage during the day and as a radiator that releases heat during the night. The summer behaviour can be verified as further research development through advanced digital monitoring and predictive instruments in the perspective of cognitive buildings. It, together with a Life Cycle Cost (LCC) analysis, can answer the question of the more convenient solution from the construction and management point of view.

Acknowledgments

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Authors contribution

M. Imperadori: conceptualization, funding acquisition, methodology, project administration, resources, supervision. N. Di Santo: data curation, formal analysis, investigation, visualization, writing original draft. M. Cucuzza: data curation, formal analysis, investigation, visualization, writing original draft. G. Salvalai: conceptualization, methodology, project administration, supervision, validation. R. Scoccia: conceptualization, data curation, validation. A.Vanossi: conceptualization, data curation, funding acquisition.

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DIGITIZATION OF BUILDING SYSTEMS USING IFC TO SUPPORT PERFORMANCE ANALYSIS AND CODE CHECKING: STANDARD LIMITS AND TECHNOLOGICAL BARRIERS. A CASE STUDY ON FIRE SAFETY

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Abstract

The study presented in this paper is part of a digitization project developed for the University of Padua. It aims at demonstrating how IFC (Internet Foundation Classes) ISO Standard can be used as a reliable data model to support Performance Analysis (PA) and code checking for construction disciplines. Fire Safety Engineering (FSE) is analyzed as a challenging test field because it highly affects different building aspects and highlights interoperability issues. The methodology proposed in the study consists in checking a digital approach to PA based on information classes that can express both users' requirements and performance specification of technical elements to develop computational code checking. This method is developed by creating virtual classes representing built systems and using relation classes and performance attributes to check if technical elements fulfil users' requirements. By forcing the model to be based on standardized information classes, the study verifies if IFC, as an ISO standard, can be used as a universal and scalable reference model for performance analysis and code checking. More specifically, the study focuses on the availability of IFC's information classes and attributes that define a PA model. This research verifies the achievement of the proposed goals for FSE (Section 2) and then highlights the interoperability limits that affect an IFC-based approach to computational FSE code checking (Section 3). Finally, the technical feasibility of the methodology's market implementation is presented (Section 4). The study's innovative approach is related to the fact that IFC is often analyzed as an information exchange format, not as a data model, where standardized relations between building ontologies can be simulated. Digital ontologies of relational aspects are experimented with by following this approach. These reports support code conformance analyses of the technical element performance specification. The study then indicates how the information modelling discipline could be shaped to encourage standardized code checking better.

Keywords

IFC, Performance analysis, Code checking, System engineering.

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1. INTRODUCTION

The performance verification of a technical element depends on the requirements that the element is expected to satisfy. These requirements can be expressed by the technological system to which this element belongs. Therefore, it is necessary to set up a compliance control policy to compare the systems' requirements and the related element's performance. Thus, the relationship between the technical element and the technological system must be communicated. At a methodological level, this approach finds equivalence in the discipline of value analysis. This discipline applied to the AEC industry (Architecture, Engineering and Construction) compares the cost of technical elements part of built systems (parametric or metric) to the performance of the systems these elements constitute (envelope, plant systems, load-bearing structures, fire prevention systems, etc.). In order to support evaluation processes in Value management procedures, there is a need to standardize the definition of Performance Analysis (PA) of building systems to compare the performances and costs of homogeneous technical solutions [1, 2].

The relation between the performance of functional units and their technical specifications is represented in the General Architecture Reference Model (GARM) [3]. This model is therefore replicated in the IFC (Internet Foundation Classes) data model published by buildingSMART, which is, at the same time, a widely diffused reference in the AEC industry and an information standard for software applications, as stated in IFC ISO 16739 standard. Concerning this aspect, there are several technological and disciplinary limits. Technical limits are related to the fact that many software applications don't fully implement the IFC data model but only a part of it. Disciplinary limits depend on the fact that building performance simulation and analysis are usually developed employing software applications that recreate disciplinary models in proprietary environments. Then, relational classes of IFC at the basis of the PA approach are not cited in published scientific works, while conceptual models representing disciplinary aspects, such as the GARM, are.

The study's methodology consists of creating virtual classes representing built systems and using relation classes and performance attributes to describe the relations between building systems and constituent technical elements. This relationship allows for developing the computational checking of technical elements' performance compliance to requirements specification.

This information modelling and code-checking technique exceeds current software limitations both in writing the *.ifc* file and reading it. The *Ifcopenshell* library (available at http://ifcopenshell.org) was tested to overhead these limits. Using this python library, IFC models can be edited and enriched when software applications can't write classes that exist in the current version of the IFC standard. The result of these tests was then validated using the application FZKviewer (available at https://www.iai.kit.edu/english/1648.php) to demonstrate full IFC compliance of the tested models to the ISO standard.

The correctness of the data model and reliability of the experimentation demonstrates that IFC, as an ISO standard, can be used as a reference model for performance analysis and code checking.

2. TEST ON IFC DATA MODEL MATURITY TO SUPPORT PA ATTRIBUTES

The test on the availability of adequate classes and attributes is organized into the following:

- analyze the availability of adequate attributes for compilation of domain-specific requirements in parent classes and then check for performance specifications attributes both in parent and child classes;
- monitor the relationship between spatial or functional superclasses and the related technical elements they host to compare a technical element's performance with the requirements of the space or system in which it is installed.

2.1. REQUIREMENTS AND PERFORMANCE SPECIFICATION IN IFC HIERARCHICAL STRUCTURES: FROM ATTRIBUTES TO THE USE OF IFCRELASSOCIATESCLASSIFICATION CLASS

In the IFC schema, most domain-specific attributes are assigned directly to constituent materials using the *IfcMaterialDefinition* resource. In this way, each technical element inherits domain-specific properties by material layer, profile or constituents. Further performance information of technical elements is given because each class hierarchically child of *IfcElement* (including *IfcBuildingElement*, *IfcSystem*, *IfcGroup*, and *IfcZone*) indicates several environmental and performance indicators.) shows several environmental and performance indicators.

To support a PA approach, spatial containment and functional superclasses should express general requirements to check if referring technical elements develop consistent performances.

To date, the validity of IFC's superclasses, such as *IfcBuilding* and *IfcSystem*, has been confirmed concerning their potential in terms of spatial organization and item instantiation. On the contrary, an effective standardization of information modelling and management regarding performance and condition assessment is not yet fully valid for the higher classes and the hierarchy of IFC.

In IFC, functional and technical systems are described using object grouping entities such as *IfcAsset*, *IfcInventory*, and *IfcSystem*. *IfcSystem* allows grouping elements sharing the same functions or objectives (construction systems, sectors, plants). This information can be defined by the Pset_ServiceLifeFactors, in which there are properties concerning the adjustment of the service life. Although the presence of these properties is appreciable, the information range is too restricted to face a fully interoperable PA methodology. The IFC implementation of classification references offers one possible solution to this limit. Further attributes can be implicitly linked using the *IFCRelAssociatesClassification* relationship. The assignation of an item to an IFC class and its reference to a classification system allows the possibility of compiling requirements, superclasses performances and constituent elements just by mapping the references in a specification matrix as the one expressed in the Specifiers Properties information exchange (SPie) [4].

2.2. FUNCTIONAL AND SPATIAL RELATIONS MAPPING

Creating relations between building elements and functional or spatial entities is fundamental for the correct setting of PA procedures. The objectified relationship, *IfcRelContainedInSpatialStructure*, is the typical procedure used to assign elements to a specific spatial structure: *IfcSite*, *IfcBuilding*, *IfcBuildingStorey* or *IfcSpace*. The IFC exporter automatically builds that relationship for both software used, Graphisoft ArchiCAD 24 and Autodesk Revit 2021. Sometimes further spatial connections are needed to trace the presence of a technical element in a spatial container such as *IfcZone* or *IfcSpatialZone*. These classes group two or more spaces by function (i.e., a fire compartment) or performance specification (i.e., thermal zone). Zones represent virtual groups of spaces that have no spatial structure assigned, while spatial zones have a spatial containment given through the *IfcRelSpaceBoundary* class. In this case, the connection is managed by the relationship *IfcRelReferencedInSpatialStructure*.

The *IfcSpatialZone* class is not yet correctly implemented in the modelling software analyzed. In Graphisoft Archicad 24, exporting this entity at all is impossible. Instead, in Autodesk Revit 2021, no system families represent the *SpatialZone*. The only way would be to create with the tool "Area" a tridimensional object and, through the *IfcExportAs* parameter, export the object as an *IfcSpatialZone*.

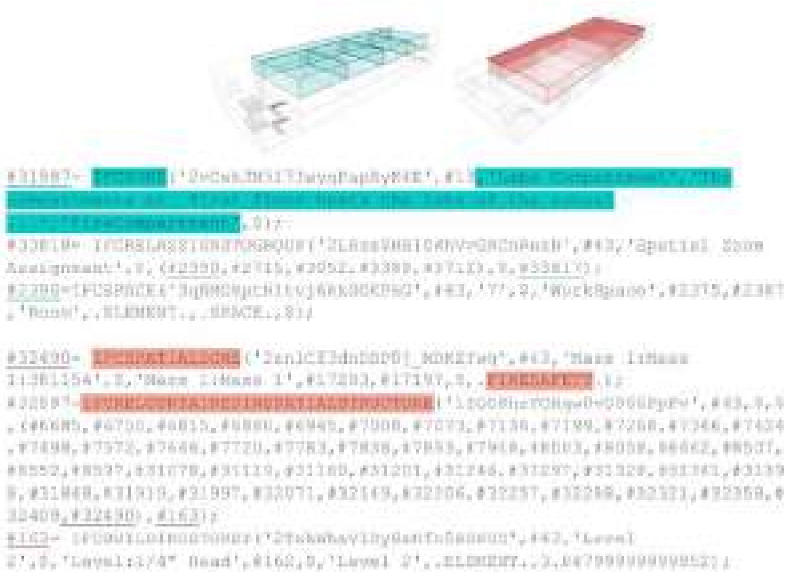

Fig. 1. *IfcZone and IfcSpatialZone in STEP file exported from Autodesk Revit 2021.*

IfcRelAssignsToGroup is used instead to aggregate spaces and entities in zones [5]. The IFC exporter manually adds that relationship for both software used, Graphisoft ArchiCAD 24 and Autodesk Revit 2021. Revit does not have a concept of architectural/fire safety zones. However, IFC zones are exportable using the shared room parameters (Fig. 1). By adding the shared text parameter "*ZoneName*" to the Revit "*Rooms*" category in the "*IFC Parameters*" parameter group, a user can specify the name of the zone that the room belongs to. Revit will then create one *IfcZone* for each unique "*ZoneName*" value and associate all the rooms with that value to that zone. In addition, the shared parameters "*ZoneObjectType*" and "*ZoneDescription*" can be used to set the object type and description of the *IfcZone*. A Revit room can be associated with up to 1000 zones by adding extra shared text parameters: including the shared parameters "*ZoneName #*" (where # = 2, 3, 4, etc.) adds more zones to a room. In addition, the "*ZoneObjectType*" and "*ZoneDescription*" parameters can also be similarly extended to, e.g., "*ZoneObjectType 2*". A room will be associated with each zone defined for that room. It is possible to export the properties of the *Pset_ZoneCommon* for a Zone, as shown in Figure 2, containing an extract of the IFC shared parameter file. However, since these parameters are associated with spaces, if a space belongs to different zones, it is not yet possible to associate Property Sets (such as *Pset_ZoneCommon*th *IfcZone*).

Other properties, such as *Pset_SpaceFireSafetyRequirements* or *Pset_SpaceOccupancyRequirements* that, according to IFC standards, could be assigned to the class *IfcSpace* or *IfcZone*; in Revit, can only be associated with spaces. A shortcut would be to use Revit's Zones in the "Spaces and Zones Panel" of the Analyze tab. However, this second way is correct only for HVAC zones. On the other hand, Graphisoft Archicad 24 exporter does not show any problems in this respect: its IFC project manager allows the creation of new spatial relations among spaces creating an IFC Zone.

Functional or logical relations between physical entities are then managed with *IfcRelAssignsToGroup* relation that can instantiate objects in any *IfcGroup* subclass: asset, inventory, or system.

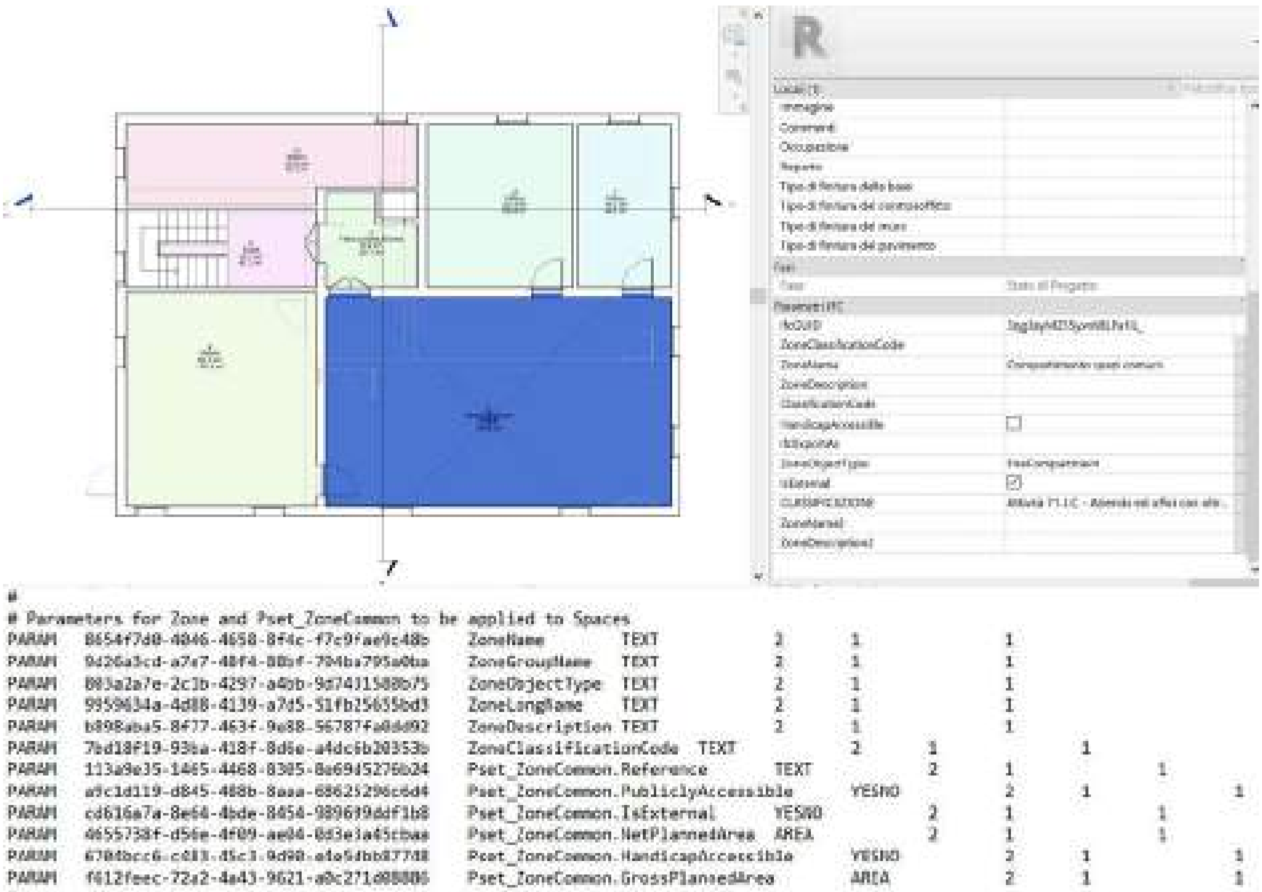

Fig. 2. *Revit IFC shared parameters.*

As demonstrated, the data model offers a complete set of possible connections so that it is possible to map any relation underlying performances of building systems and activate class-based PA procedures.

3. INTEROPERABILITY LIMITS

Not many types of software write the relations highlighted before, and even fewer can show their presence in a graphical or hierarchical representation. Besides the limits of information mapping and visualization, it is relevant to highlight that the maturity of the data model is higher than the possibility of writing those classes using commercial software applications. Several types of software do not read all the classes and attributes of IFC. Therefore, these applications can't develop PA procedures based on the methodology proposed. These issues are irrelevant to the study because they depend on the IFC certification of each software. As tested, every application can solve these issues just by adding some libraries to read the full schema, as well as official IFC visualizers do. The evidence of this statement is supported in this work by the successful editing of IFC files through the *IfcOpenShell* library and the correct and verified visualization of the information in FZK Viewer, as visible in Section 4.

As mentioned, the problem is to gather information about building elements' performances and compile system requirements specifications to verify if the design complies with national codes. The following part of the study shows the methodological problems that arise when translating a discipline into IFC, in this case, the FSE discipline. These are divided into three groups:

- property definition;
- spatial and functional requirements;
- functional and logical representation.

Most of the issues mentioned are related to code-based relations, but it is relevant to analyze IFC capability to map those relations to support model checking.

Fire Safety Engineering discipline is analyzed as a representative example that embodies all of these issues but, on the other hand, highlights how IFC can possibly collect system and building data to support fire safety engineering (FSE) and fire safety monitoring.

3.1. DOMAIN-SPECIFIC PROPERTY DEFINITION

Several studies have highlighted the potential and weaknesses of IFC concerning FSE [6]. Data model analysis shows that *IfcMaterial*'s PropertySets provide thermophysical properties of a building element and fire-specific properties. Instead, the common PropertySets of *IfcBuildingElement* subtypes contain properties defined for regulatory or standardization purposes, such as *Fire Rating*, *FlammabilityRating*, *SelfClosing*, *SmokeStop*, *Compartmentation*, *SurfaceSpreadOfFlame* [7]. On the other hand, the definition of the fire reaction in IFC needs clarification. The *FlammabilityRating* property is only attributed to the class *IfcCovering*, while *FireRating* is attributed to all the *IfcBuildingElement* subclasses.

Furthermore, the property *Combustible* is assigned to elements with a two-dimensional extension. The *FireRating* property can be used to define the resistance to fire, and the *FlammabilityRating* property defines the reaction to fire. The only class which covers all three properties is *IfcCovering*. However, the potential contribution of a product to a fire does not only depend on the covering, but the underlying layers could also influence it. Three scenarios are possible (Fig. 3):

- a generic wall with a structural package is exported through the class *IfcWall*, and an architectural package is exported with the class *IfcCovering*, to which it is assigned the property *FlammabilityRating*;
- a generic wall where the structural part also coincides with the architectural part. An example would be an XLAM wall that constitutes an important fraction of the total compartment area and must be treated as structure (fire resistance) and cladding (reaction to fire). In this case, to map its reaction to fire in an IFC model, it is necessary to create a fictitious layer outside the wall exported as *IfcCovering* to which the *FlammabilityRating* property is associated;
- an internal partition must be exported as an *IfcWall* of type Partitioning. Again, to map the fire reaction of the partition, it is necessary to create fictitious *IfcCovering* layers.

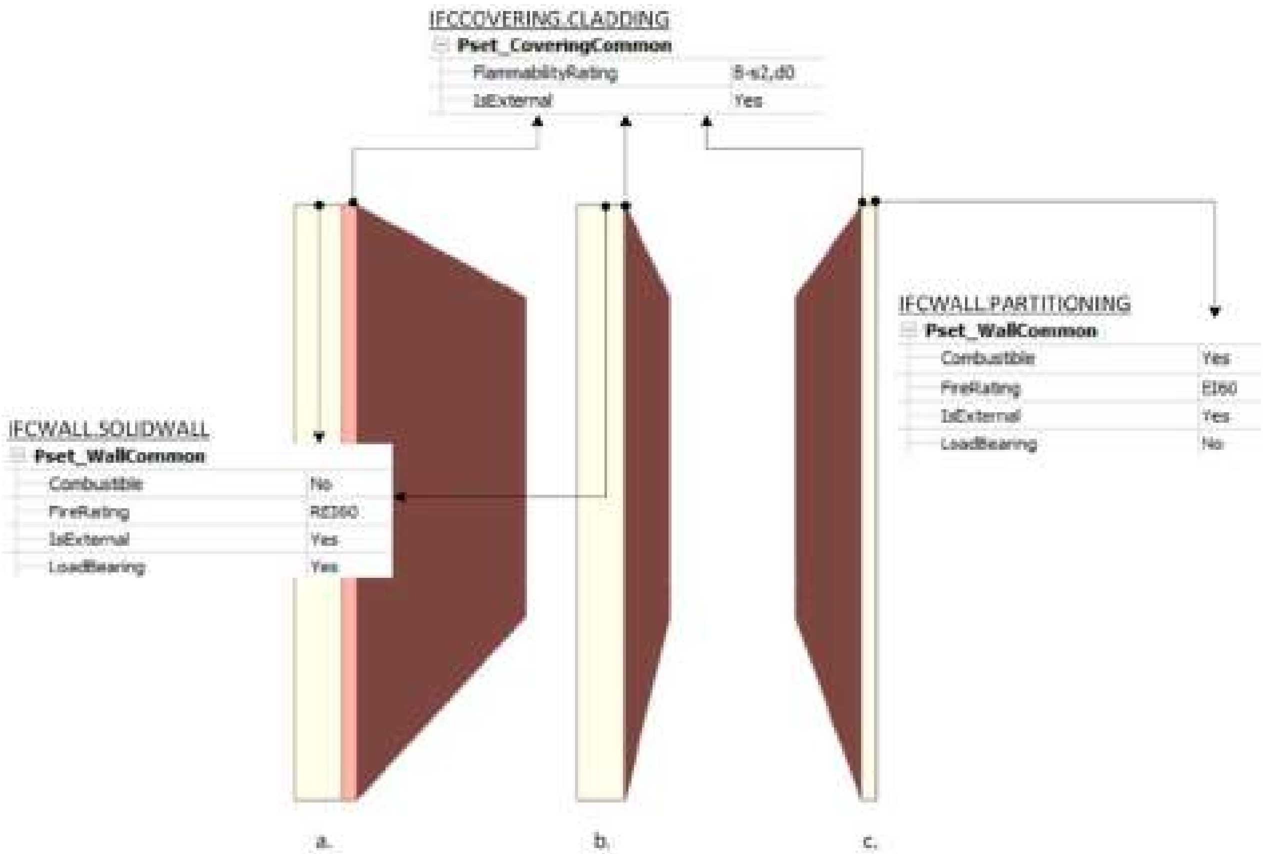

Fig. 3. *Export of Pset_CoveringCommon and Pset_WallCommon.*

The first scenario is the right way of modelling a wall consisting of a structural layer, which generally does not require a reaction-to-fire classification, and an architectural refacing that does.

The problem with the last two scenarios is that they force the modeller to create fictitious entities to map the wall's fire reaction into the model. Ideally, we would like to be able to implement the property set *Pset_WallCommon* with a new parameter to map the fire reaction of the wall as well.

Consequently, IFC development and the disciplinary ontological definition must address domain-specific property definition.

3.2. DETAILED OR RULE-BASED SPATIAL AND FUNCTIONAL REQUIREMENTS

Following the European directives, Italian legislation (Ministerial Decree n. 256, 2019) defines subject activities, which can be contained in a building, part of a building or several buildings.

Presidential Decree n. 151, 2011, contains a list of 80 activities subject to Fire Brigade control. Each activity includes assigned subclasses and risk categories (cat. A, B, and C) based on the severity of the risk rather than the size or degree of complexity of the activity itself.

IFC translation of this kind of entity prefers the entity *IfcZone*, compared to *IfcBuilding*, since it defines «groups of spaces, partial spaces or other zones». The deprecation of the MainFireUse property of *IfcBuilding* class, from the IFC4.1 version, avoids defining the activity category through *IfcBuilding* class and involves the use of the entity *IfcZone* that is therefore specified as a "FireCompartment".

As specified in Building Smart Knowledge base, «in case of a zone denoting a (fire) compartment, the following types should be used, if applicable, as values of the *ObjectType* attribute: '*FireCompartment*': a zone of spaces, collected to represent a single fire compartment. - '*ElevatorShaft*': a collection of spaces within an elevator, potentially going through many storeys. - '*RisingDuct*':

A collection of vertical airspaces. - '*RunningDuct*': A collection of horizontal airspaces».

As mentioned in Section 2.1, this entity can be further and better specified through *IfcClassificationReference* class, thanks to the *IfcRelAssociatesClassification* relationship. By using this class, information regarding the subject activity can be shared with IFC hardcoded attributes.

Similar problems arise when fire compartments have to be digitized. In the FSE discipline, for instance, a fire compartment can coincide with a room, a zone, several parts of a building story or the whole building. These can be exported using IFC*Zone* or *IfcSpatialZone* classes. They share some *PropertySets* like the *Pset_SpaceOccupancyRequirements* with properties such as *OccupancyNumber* or *OccupancyType* and the *Pset_SpaceFireSafetyRequirements* defining, for instance, the risk factor or the equipment of sprinkler systems. On the contrary, the control of the protection level of the compartments is not completed. Currently, no properties can store a compartment-specific fire load calculation. Other weaknesses are typically linked to the Italian context, such as the definition of risk profiles.

The fire risk profiles, *Rlife*, *Renv*, and *Rprop*, are simplified indicators to assess the fire risk as stated by Ministerial Decree n. 256, 2019.

In these cases, it is necessary to introduce a user-defined *PropertySet* containing properties such as *IsSmokeProofCompartment* (of Boolean type), *SpecificDesignFireLoad* (the unit is MJ/m^2 and therefore it will be specified as «UserDefined» since this unit of measurement does not currently exist in IFC), *Rlife*, *Renv* and *Rprop* (of type *IfcLabel*). Obviously, to guarantee interoperability between IFC and BPS (Building Performance Simulation) tools, user-defined PSet needs to be avoided.

3.3. FUNCTIONAL AND LOGICAL REPRESENTATION LIMITS AND ISSUES

Systems modelling and management requirements matching are necessary to map the functional connection of different systems to the zones of the building they serve. Terminals of the piping system for fire suppression are assigned to the *IfcFireSuppressionTerminal* class and further specified through the *PredefinedType* attribute. This class is part of the *PlumbingFireProtectionDomain*. On the contrary, segments composing the piping system for fire suppression are included in *IfcPipeSegment* class which is part of *IfcHvacDomain*. Segments are then grouped in an *IfcDistributionSystem*, which needs to be specified through the enumerative type «*fireprotection*». The system is therefore specified by its reference (*Pset_DistributionSystemCommon*) and its service life attributes (*Pset_ServiceLifeFactors*). *IfcDistributionSystem* class is part of *IfcSharedBldgServiceElements* placed in the interoperability layer of The IFC schema. This means that the translation in information classes of a discipline is not limited to a single domain but needs to collect classes coming from different domains, some of them correctly placed in the interoperability layer and there specified, others part of misleading domains as demonstrated with reference to the *IfcPipeSegment* example.

As well, it is crucial to represent logical connections. In addition to the spatial containment concept template, IFC offers several connections grouped in the object composition template (aggregation or nesting) or the object connectivity template (element connectivity, space boundaries and spatial structure).

Hierarchical representation if IFC does not express logical connections between rooms. This constraint is relevant, for example, in escape route checking, and IFC has no entities and properties concerning the escape route. To overcome the lack of the standard relating to FSE, BuildingSMART launched a project to improve information exchange for Occupant Movement Analysis (OMA) and Fire Dynamic Simulation (FDS), as available online at: https://www.buildingsmart.org/standards/calls-for-participation/fire-safety/.

The design of escape routes has several specific definitions for which the data model is not yet ready. These include dead-end corridors, open, protected, or smoke-proof routes, emergency exits, etc. IFC domain only allows the extrapolation of geometrical information of escape routes (width or length) or the possibility to define which rooms are included in them (with the Boolean property *FireExit*) [6]. This enables the creation of spaces that can be identified as escape routes and then integrated with additional information.

As a result of all these disciplinary limits, the information exchange takes place through manual data entry into specific fire prevention software, e.g., in the definition of Fire Dynamic Simulation (FDS) [7, 8].

This statement points attention to the severe limits to the implementation of IFC as a reference model for fire safety policies and as well as for supporting BPS in FSE. A barrier to implementing the IFC solution is the dependence of engineering procedures on national regulations set on unstandardized assumptions. Hence, the use of IFC can be increased by setting harmonized national standards by higher authorities.

4. IMPLEMENTATION TEST: IFC RELATIONS-BASED FSE CODE CHECKING OF ESCAPE ROUTES

Although the IFC data model has several weaknesses regarding the standardization of escape systems, an approach that relies on assumptions based on the existing IFC dataset was proposed.

Escape routes are unobstructed routes for occupants to reach a safe place and are all part of an escape system made of stairs, corridors, moving walkways, ramps, safe places, exits, doors, safety lighting, signs, etc. The basic idea of this approach is to use the class *IfcSystem* to group all those elements along an escape route through the relation *IfcRelAssignsToGroup* (Fig. 4). All spaces, doors, and stairs belonging to the system will have the boolean property *FireExit* set to *TRUE*. The *IfcRelAssignsToGroup* relation is merely a grouping of elements; then, it avoids the identification of the space sequence along the escape route. This can be achieved through other relations such as:

- *IfcRelSpaceBoundary*, which relates a space (*IfcSpace*) to the physical elements that delimit it, such as a door (*IfcDoor*) (Fig. 5);
- *IfcRelContainedInSpatialStructure* allows for the connection of a physical element, such as a stair *(IfcStair)*, with a space *(IfcSpace)* (Fig. 6).

Escape routes are distinguished according to their degree of protection and compartmentalization concerning the rest of the spaces. They can be protected, smoke-proof, external, or unprotected. Additionally, when entering an escape route with a single directionality, the spaces that make it up must have the same protection level. Identifying escape route segments with the same protection degree is crucial. Indeed, an escape route can lead directly to the emergency exit and another escape route with a higher de-

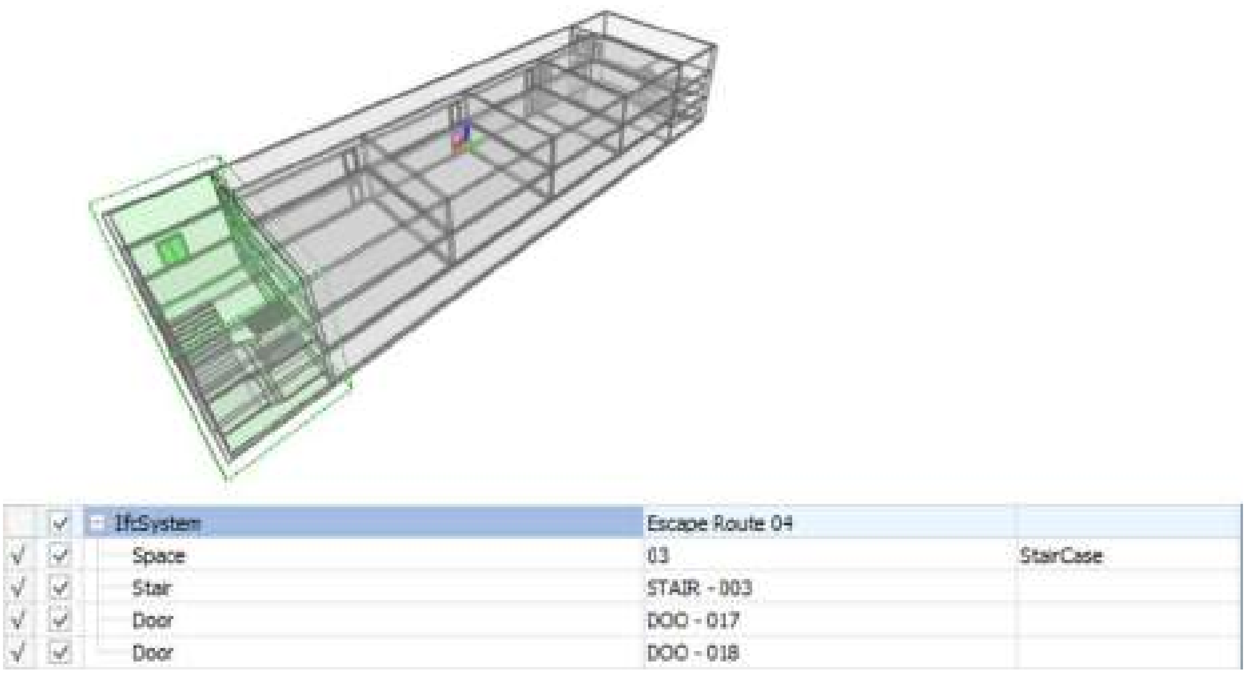

Fig. 4. *Entities grouped in an IfcSystem representing an escape route.*

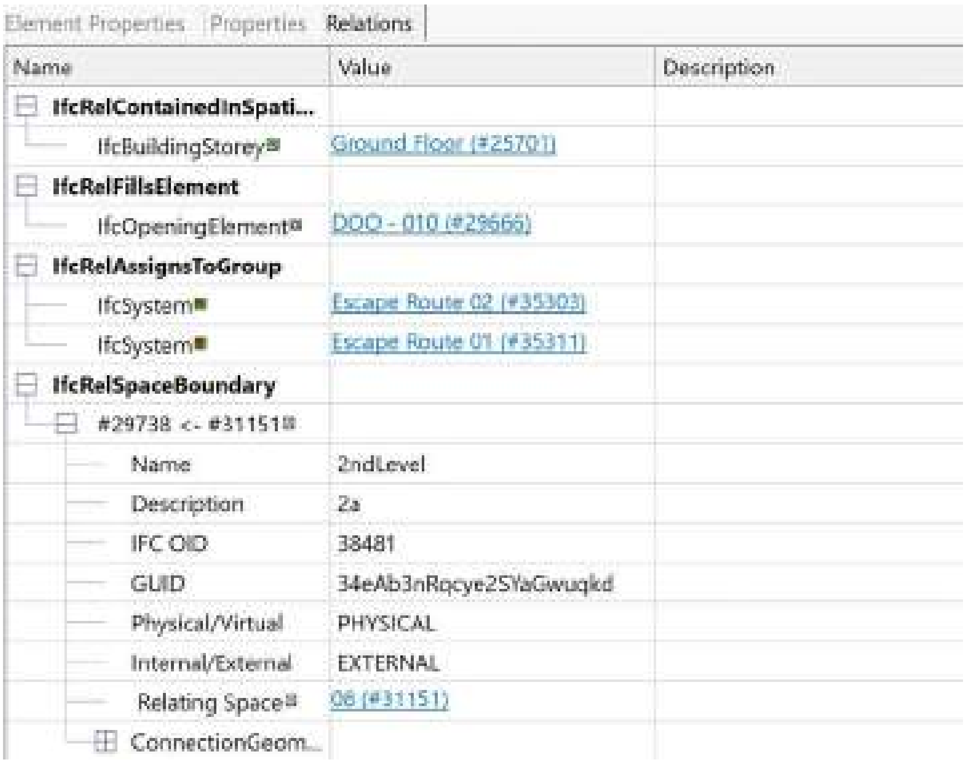

Fig. 5. *IFC relationship assigned to the IfcDoor entity: the data model can express its belonging to different systems.*

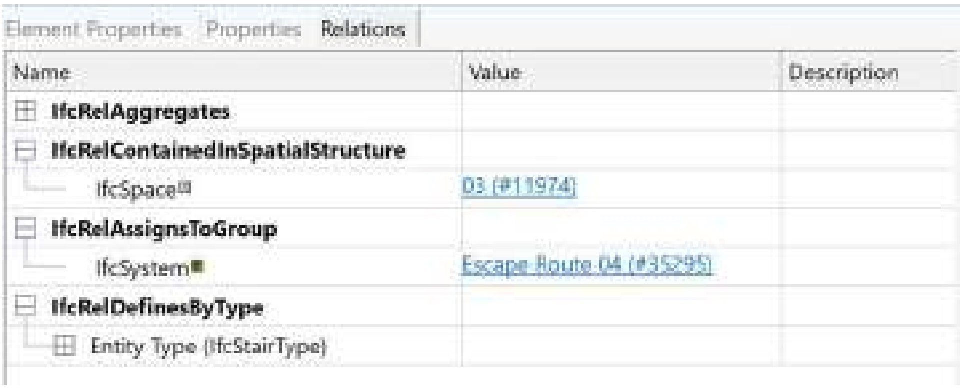

Fig. 6. *IFC relationship assigned to the IfcStair.*

gree of protection. For example, in a multi-storey building, each floor may have a protected corridor leading to a smoke-proof staircase. The approach proposes to create as many *IfcSystem* as there are one-way sections of escape routes with different levels of protection, and an *IfcSystem*, which groups all of them together through the relation *IfcRelAssignsToGroup* (Fig. 7). Besides, the *ObjectType* attribute might help to define whether the escape route is smoke-proof, protected, or unprotected.

Furthermore, the objectified relationship via *IfcRelReferencedInSpatialStructure* can be used to connect a system to the relevant spatial element that it serves. This allows coupling the escape system to compartments (*IfcSpatialZone*) or spaces (*Ifc*Space) (Fig. 7).

Finally, the strategy allows automating the calculation of the escape route length by filling two new properties for the *IfcDoor* entity of a *User-Defined PropertySet* (*Pset_EvacuationRequirements*):

- *PreviousExitLength* is used to define the distance to reach the emergency exit;
- *NextExitLength* is used to specify the length of the next emergency exit or, in the case of a final exit door, the distance to the safe place.

Element Properties | Properties | Relations

Name	Value	Description
IfcRelAssignsToGroup		
IfcSystem	Escape Route 01 (#48164)	
IfcSystem	Escape Route 02 (#48156)	
IfcRelServicesBuildings		
IfcSpace	07 (#25837)	
IfcSpace	05 (#26128)	
IfcSpace	04 (#26270)	
IfcSpace	06 (#25986)	

Fig. 7. *IFC relationship assigned to the IfcSystem.*

As previously expressed, the problem seems more related to the higher classes of IFC that host a limited number of property sets and force to outline user-defined ones, but the methodology proposed is consistent.

5. CONCLUSIONS AND FUTURE WORK

Testing of the methodology highlighted the potentialities of IFC and the correctness of the approach in supporting PA procedures. The method is independent of technical implementation issues, as demonstrated by the correct visualization in validation tools of IFC models that are extended with the above-mentioned relations.

This study shows that activating a PA and a code-checking policy in computer-aided engineering requires investment in standardization. Therefore, it is crucial to capitalize on the availability of a consistent data model as it is offered by the standard ISO 16739. On the other hand, severe limits occur in FSE information exchange, and this limit affects a sustainable digital management policy.

The study clarifies that the above limitations in information exchange depend on standardization processes that are not dependent on IFC. IFC could play a significant role in the future to help harmonize existing standards.

In addition, IFC expresses strict limitations as a data model suitable to collect building system performance. As articulated in the research, the higher levels of the building hierarchy have limited "PropertySets". For this reason, collecting the performance data of technical elements in building system performance is problematic. In addition to the lack of best practices shared in literature, this problem leads to a limited culture of PA procedures based on IFC standards, even if it can be considered methodologically consistent.

The development of this work will allow finding procedures and applications to write the IFC database. Currently, some methods are theoretically allowed but not assisted by major software applications. Future work must be dedicated to implementing the methodology in different disciplines to test the robustness of the data model and the procedure.

Acknowledgments

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Authors contribution

M.G. Donatiello: analysis on IFC data model in relation to spatial containment, functional systems and relation classes. A. Gabbanoto: analysis on FSE code checking based on IFC classes. C. Zanchetta: definition of IFC based procedures, text editing. R. Paparella: project coordinator, text revision.

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PREVENTING COVID-19 SPREAD IN SCHOOL BUILDINGS USING BUILDING INFORMATION MODELLING: A CASE STUDY

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Abstract

During the last years, many studies focused on automated processes for compliance checking intended to replace the current design verification practices. So far, the verification of projects in the Architecture, Engineering, Construction, and Operation industry has largely consisted of manual processes, which result in laborious, costly, and error-prone. The compliance checking process addresses the project's whole life cycle, from the design phase to the end of life. Previous researches show the applications of a Building Information Model Checking referring to the compliance with several national and international normative to meet standards requirements. This paper proposes an innovative approach to evaluate the compliance of school buildings with the measures to prevent and control the spread of Coronavirus, one of the most significant pandemics. A case study is then presented to validate the method. The school building is modelled using Revit software. Dynamo is employed as a visual scripting tool to customize the mathematical formulations of each safety rule from different standards for COVID-19 prevention. Revit and Dynamo are coupled to conduct the compliance checking. The methodology herein proposed allows for verifying the school environments showing their compliance with safety standards. Although the World is coming out of the COVID-19 pandemic, this approach could be used to face other waves or different types of pandemics.

Keywords

Building Information Modelling, Visual Programming Language, Code checking, COVID-19.

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1. INTRODUCTION

Coronaviruses (CoVs) are enveloped positive-strand ribonucleic acid viruses that can infect humans and animal species [1]. The Chinese Centre for Disease Control and Prevention confirmed a novel coronavirus named severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), closely related to CoVs and highly contagious [2]. The World Health Organization (WHO) declared a public health emergency of international concern on 30 January 2020, and the disease named "COVID-19" was then announced [3]. To date (April 2022), there have been more than 500 million confirmed cases and more than 6.4 million deaths confirmed by WHO [4].

In such a scenario, healthcare systems, infrastructures and educational systems face great challenges in providing essential services. Governments have immediately implemented emergency plans to deal with the pandemic trying to reduce the impacts on people's mental and physical health and financial resources. This results in issuing different guidelines to face the virus spread. Rigorous programs to control the infection are needed to minimize the risks of COVID-19 spread, while new ways of working support the recovery of essential services during the pandemic. Adopting organizational, environmental and personal measures optimizes emergency management allowing for normal activities and reducing the contagion risk among people [5]. The main center for research, control and technical-scientific consultancy in the field of public health in Italy (Istituto Superiore di Sanità, ISS) has defined behavioral rules for personal protection, such as the use of masks and gloves, social distancing and hand sanitation with alcohol-based products. ISS published *Guidelines for the prevention and management of indoor environments in relation to the transmission of the SARS-CoV-2* [6].

In Italy, schools have implemented several processes for the re-functionalization of spaces in order to make them usable during the COVID-19 pandemic. School buildings must respect specific rules to be safely used. The non-compliance with regulations might compromise the quality of the built environment and the quality of the services delivered, which can impact health [7]. Furthermore, compliance issues could lead to delays in design, extra costs, as well as project reworking and poor quality [7]. For example, bigger classrooms were built by breaking down dividing walls, or new classrooms were created using corridors. Considerable resources were spent to adapt and use different buildings when this was not technically feasible. If these approaches were not possible, the students would take turns with a reduction of school hours.

The aim of this paper is to define a practical method to automatically check the school buildings compliance with the measures to prevent and control the spread of Coronavirus using the Building Information Modelling (BIM) approach. BIM is able to optimize processes and obtain higher quality products and performance by managing data requirements in an alphanumeric way, for example, through code-checking procedures. 3D-BIM models can also be coupled with Visual Programming Language (VPL) software tools to perform advanced compliance-checking processes. Here, different guidelines for struggling with the spread of COVID-19 were analyzed, and control scripts were modelled using VPL scripting. BIM-VPL coupling is then used to analyze the performance of buildings and evaluate optimal use conditions of school buildings. Then, this study provides a suitable methodology to counter the epidemiological diseases spread within the working environment in general, as it is replicable depending on different types of parameters adopted.

2. BIM AND VPL APPROACH

COVID-19 has dramatically affected the world economy, industry, and citizens. Nevertheless, digitization is aiding many businesses to adapt and overcome the current situation caused by the pandemic [8].

Building Information Modelling (BIM) is one of the most promising developments in the Architecture, Engineering, Construction and Operation industry [9–15]. BIM consists of expanding 3D models to computable nD models capable of simulating each building's lifecycle process: planning, design, construction, and operation. 3D BIM concerns not only modelling buildings, infrastructures or services: it allows for performing specific analyses based on the geometrical information of the model, such as 3D visualization, clash detection and code checking. Clash detection is the analysis of possible geometric interferences among objects, models and drawings, while code checking is the analysis process of potential data inconsistencies between objects, models and drawings compared with rules and standards [16]. So far, the process of checking these parameters in the industry has largely been manual, laborious, costly, and error-prone [17–19]. Object-oriented and parametric modelling provides a way to automate code-checking procedures in building designs, as it is possible to associate parametric rulings to the elements that compose the virtual model, ensuring the process runs correctly [20].

Opportunities exist to extend building performance simulations and code-checking processes with scripting environments. Visual Programming Language (VPL) software tools are now considered of high potential since they have geometric modelling functionalities together with scripting capability based on a simplified user interface. Most design tools support one or more scripting environments and are able to use a VPL as middleware bi-directionally linked to BPS tools, which results in an integrated dynamic model [21]. Actually, VPL could also be used as a BPS tool since it provides the capacity for scripting. Tools like Dynamo allow for more complex rules to be created without adding the need to code programming. For example, Röck et al. [22] established an automated link between the LCA database and the BIM model using Autodesk Dynamo as a visual scripting software. The authors calculated the environmental impacts of the case study building directly in Dynamo. Cavalliere et al. [23] use VPL tools to conduct code compliance checking to evaluate building flexibility levels by introducing six selective criteria in a BIM environment. In that case, different algorithms are implemented in a VPL tool, which is bi-directionally linked to the BIM environment where the BIM elements already host the semantic information required.

Code checking has been the subject of scientific research for years and has been put into practice in numerous projects [24]. However, no studies have focused on the use of BIM and VPL to deal with an epidemiological pandemic from the side of buildings design, which is the goal of this paper.

3. METHOD

The aim of the study is to define a practical ruleset for school spaces design in accordance with the safety measures tackling the SARS-CoV-2.

The method consists of three main steps. The first step is discussed in Section 2.1. It aims to define the relevant safety rules to be applied to school buildings. Mathematical formulations are provided for each ruleset, and they are based on Operational Manual and Guidelines. In the second step (Section 2.2), a BIM model of the Michelangelo school building is developed with Autodesk Revit. Step three (Section 2.3) concerns the application of the operational safety rules through the Code Checking process. In particular, the checks are carried out by identifying customized algorithms implemented in Dynamo software. Specific additional parameters are implemented in the Revit model to allow the performance of the scripts. Then, BIM software is linked to VPL software to perform the calculation automatically, as shown in Section 2.4. Autodesk Dynamo is employed as a visual scripting tool to customize the mathematical formulations of each safety rule. The scripting tool automatically performs the calculation by reading the design properties and geometry from the BIM. The methodology can be implemented not only in reference to the present case study, which is the compliance to the standards identified for the prevention and mitigation of epidemiological diseases. In fact, the present method can be applied according to any buildings' needs, such as regulatory updates or exceptional occurrences.

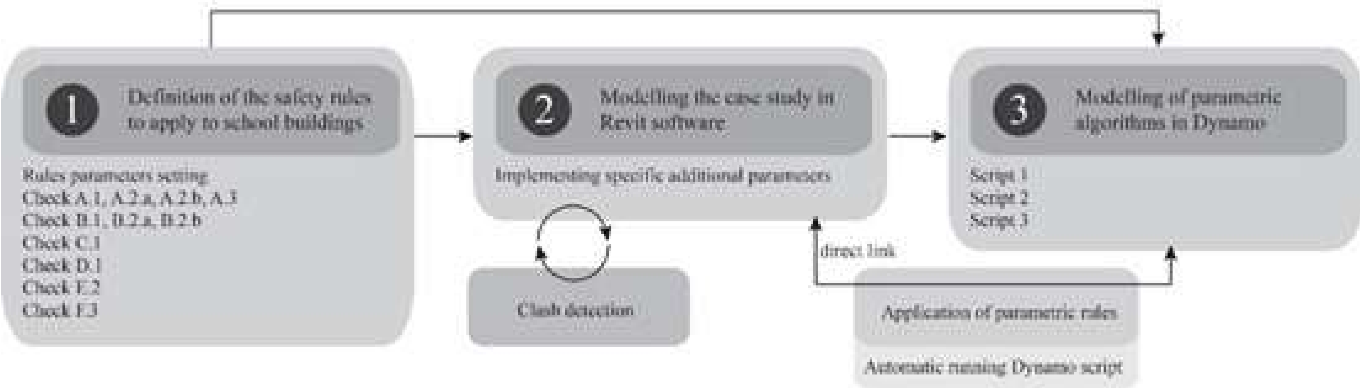

Fig. 1. *Research method.*

4. CASE STUDY

The case study is the Michelangelo Secondary School in Bari, Italy. It was built in the 1990s with a load-bearing masonry structure with bricks in porous clay. The building has a basement and three above-ground floors for a total gross area of approximately 7000 m². The upper ground floor hosts the administrative offices. The auditorium, the laboratory, a secondary atrium, the toilets and the gym extend northern. On the western side are a classroom for support activities and a laboratory. Finally, to the south is the lecturers' room, a secondary room, the infirmary and the toilets. The next two floors are for classrooms and can be reached via two internal stairs. On the first floor, there are fourteen classrooms and three laboratories, while on the second floor, there are twelve classrooms. The basement consists of the caretaker's accommodation, a refectory, the gym, the changing rooms, and the office of the physical education teachers.

4.1. DEFINITION OF SAFETY RULES

The trend of infections has forced Italian Institutions, in certain periods of higher risk, to close school buildings and apply E-learning through online classes. Once the epidemiological curve fell below the pre-established safety levels, it was possible to return to opening school buildings while considering the necessary precautions and enforcing general rules for safety. The operational rules about the schools' spaces used for this paper come from different operating manuals: the guidelines of the Veneto and Lazio regions, the ISS documentation, and the Italian Scientific Technical Committee guidelines. According to the safety guidelines, the following Table 1 shows the checks performed for the different environments considered.

Locals	Script	Checks	Criteria
A Classroom	**Script 1**	*A.1.* Distance check between fixed scholars' seats	Minimum distance between scholars = 1m
	Script 2	*A.2.a.* Dynamic zone dimension check	Minimum dynamic zone dimension = 2.5m
		A.2.b. Rime buccali distance check between teachers and scholars	Rime buccali distance between teachers and scholars = 1.5m
	Script 3	*A.3.* Maximum room capacity check	Room area on area per person (equal to a circle of radius r = 1m) = maximum room capacity
B Laboratory	**Script 1**	*B.1.* Distance check between fixed scholars' seats	Minimum distance between scholars = 1m
	Script 2	*B.2.a.* Dynamic zone dimension check	Minimum dynamic zone dimension = 2.5m
		B.2.b. Rime buccali distance check between teachers and scholars	Rime buccali distance between teachers and scholars = 1.5m
C Auditorium	**Script 1**	*C.1.* Distance check between seats	Minimum distance = 1m
D Staff room	**Script 1**	*D.1.* Distance check between fixed teachers' seats	Minimum distance = 1m
E Connecting spaces	**Script 2**	*E.2.* Connecting spaces dimension check	Area per person > 1.25 m²
F Gym	**Script 3**	*F.3.* Maximum room capacity check	Room area on area per person (equal to a grid of 2m x 2m) = maximum room capacity

Table 1. *Summary of the scripts applied to the different locals.*

4.2. MODELLING THE CASE STUDY

The building modelling has been carried out using Autodesk Revit software, starting from two-dimensional CAD drawings. Within the BIM, the spaces listed below are modelled according to the layouts used earlier than the application of the measures for containing the virus: A) Classroom; B) Laboratory; C) Auditorium; D) Staff room; E) Connecting spaces; F) Gym.

4.3. MODELLING OF PARAMETRIC ALGORITHMS IN DYNAMO

After modelling the case study and identifying standards to be applied, the following scripts are implemented in Dynamo. The Script n. 1 (distance check) allows verifying the safety distances between the fixed individual locations. The scripts aim to determine which stations can be used safely and which should be left free. Results can be displayed graphically and textually in Revit environment using the appropriate nodes shown in the figure below.

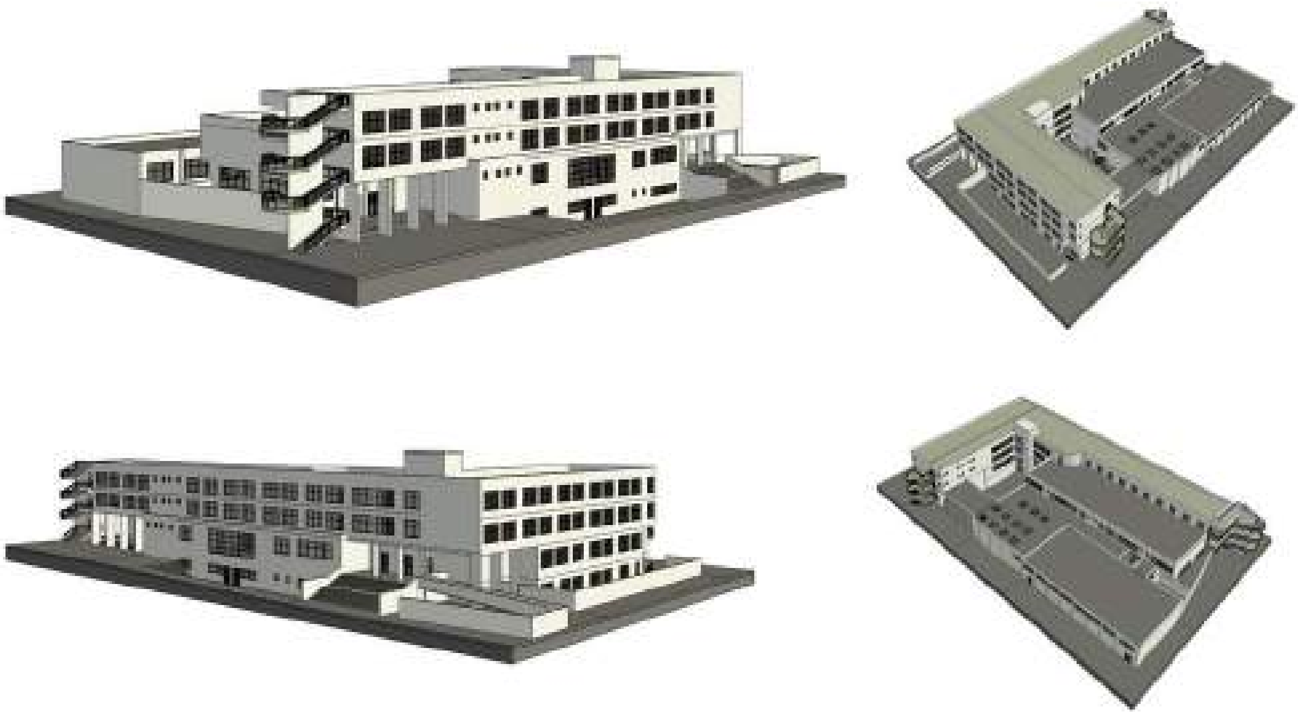

Fig. 2. *Revit Model.*

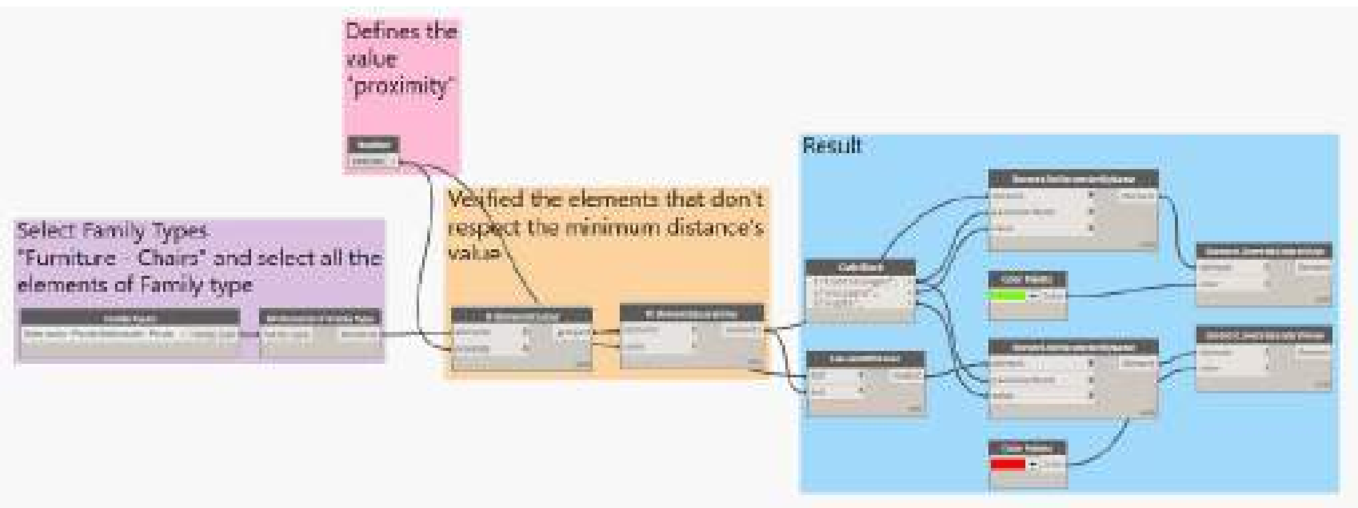

Fig. 3. *Script 1.*

Script n. 2 (critical areas dimensions check) allows verifying that the room's dimensions do not exceed the limit laid down in safety guidelines to mitigate crowding risk. The script consists of two parts: the first one concerns the identification of room lengths and widths; the second one allows checking whether the room's lengths and widths comply with the minimum values set. Results can be graphically displayed in Revit environment through the objects colors. Results are also textually shown in the properties of model "rooms" (rooms are identified as objects with several properties in Autodesk Revit).

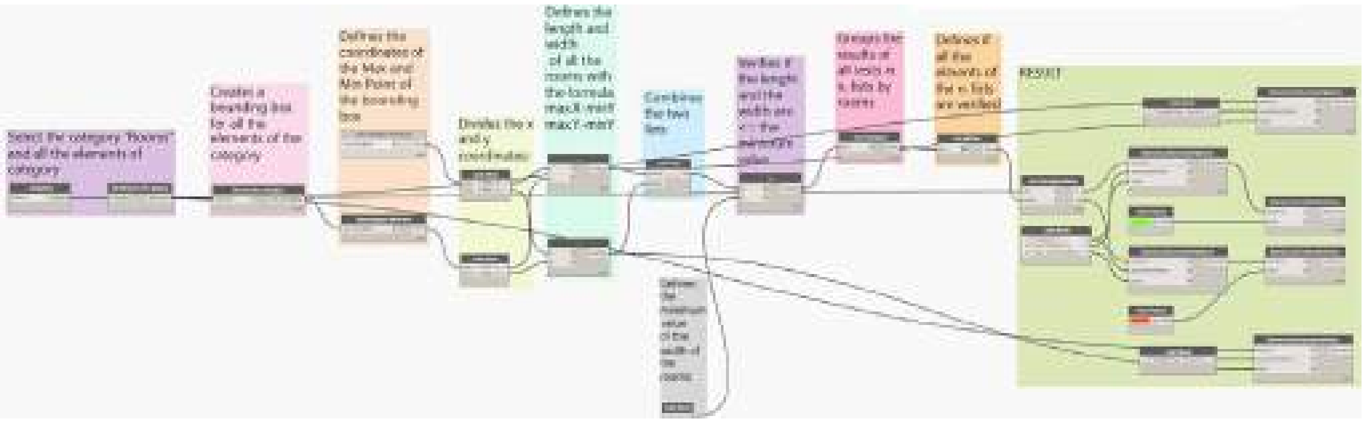

Fig. 4. *Script 2.*

Script n. 3 (maximum occupancy check of rooms) allows verifying the maximum space occupancy according to the safety rules on social distancing. Each zone is identified as a "room" in the Revit environment. The script analyzes all the rooms in the BIM model.

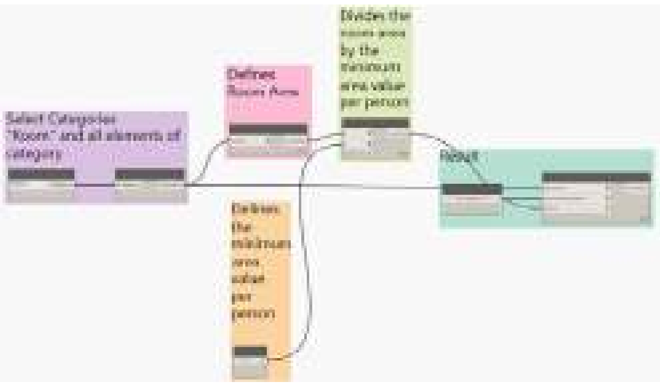

Fig. 5. *Script 3.*

Before performing the code-checking process, it is necessary to carry out a preliminary phase in order to ensure the correct script functionality: the model validation phase. This phase consists of implementing customized parameters into the BIM model to perform the code-checking activity. For the present case study, shared parameters are used, which can be written on independent files to be reused in any project and Revit family objects. Thereby, it is possible to implement these specific parameters in different BIM models to perform similar checks. Hence, the reproducibility of the present method in other case studies is guaranteed. Here, the shared parameters implemented in the BIM model are the following:

- occupancy: maximum allowed number of people in a room, which is determined by the ratio between the net area and the allowed area per person;
- room width/room length: width/length of the dynamic space identified within the different rooms or the space between teachers and scholars;
- seats distance: distance between fixed positions in a room.

4.4. OPERATIONAL APPLICATIONS TO COUNTER SARS-COV-2

Once the scripts for code-checking activities were identified, they were applied to the information model. First, the checks are carried out on the rooms' generic layout to verify the compliance with the guidelines for the containment of the Coronavirus. Then, the same verification is applied to the same rooms with a new layout meeting the indications for the prevention of the virus spread.

4.4.1. CLASSROOM: CHECK A.1

Considering the public school Michelangelo in Bari, classrooms have the same layout and dimensions in most cases. Hence, only one kind of classroom is analyzed here to show the proposed methodology.

The first check carried out concerns the compliance with the safety distances in the static area, which is the area intended for students. First, the check is carried out on a layout representative of the real state of a generic classroom of the building under investigation. Applying the proposed algorithm shows that the school benches' position in the real condition does not comply with the safety rules for preventing the spreading of the virus. As illustrated in the figure below, the algorithm highlights in red color the stations to be kept free to meet guidelines requirements.

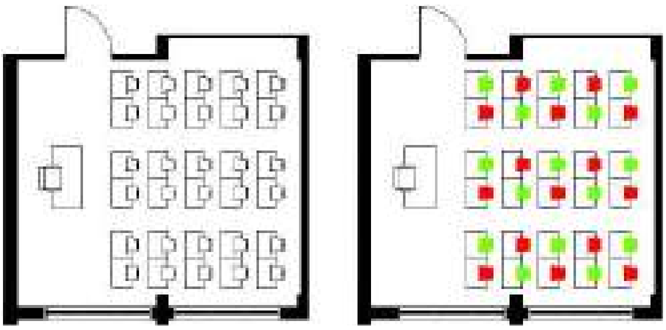

Fig. 6. *Left: layout of the room in the real condition; right: the graphic result of the check application.*

Subsequently, the design criteria necessary to mitigate the virus spread are applied to the aforementioned layout. Here, three different scenarios are taken into account:

- first scenario: precautionary scenario, which involves the distance between benches rows equal to 1 m, while the distance between benches columns equals 0.6 m;
- second scenario: in this case, the distance between the students' *rime buccali* (namely the distance between the mouths of two close people) is set as a reference measure of 1m, while the distance between benches columns is equal to 0.6 m;
- third scenario: in the last scenario, benches are arranged in double rows in order to ensure a distance between the *rime buccali* equal to 1 m; then, benches lines are interspersed with a corridor with a minimum width of 0.6 m.

The check applied on the new layouts returned a positive result in all three scenarios showing that stations can be used safely. BIM processes allow for immediate comparisons between different design alternatives. As such, designers have an effective process to perform the best possible solution. In particular, the real-time comparison between the different scenarios would allow for increasing classroom occupancy: although all three new proposed scenarios meet the rules on social distancing, the application of the third scenario allows to host 20 scholars, which is 5 more than the first scenario. This condition could ensure that all students take a class instead of e-learning lessons. If the classroom layout cannot be modified, the automated check identifies the workstations to be kept free to meet the social distancing rules, which are then labeled with red color by the algorithm proposed, as shown before.

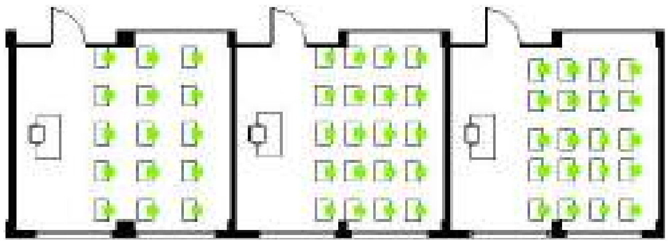

Fig. 7. *From left to right: scenario 1, scenario 2, and scenario 3.*

4.4.2. CLASSROOM: CHECK A.2.A

The classroom's dynamic space is the area between the wall behind the blackboard and the *rime buccali* of students from the first line. In order to define the dynamic zone in Revit, a "Room" is created within the classroom to circumscribe this specific zone. The script applied in this case automatically returns the width and length of each school building's room labeled as a dynamic zone. Then the script returns a result of compliance or non-compliance with the safety rules considered.

Checks are first carried out on the layout representing the typical classroom of the school building. Subsequently, checks are carried out on the layouts analyzed in the previous Check A.1.a. In particular, the changes consider the dynamic space distance of 2.5 m (Tab. 1). Here, checks reported positive results for both the typical and redesigned layout.

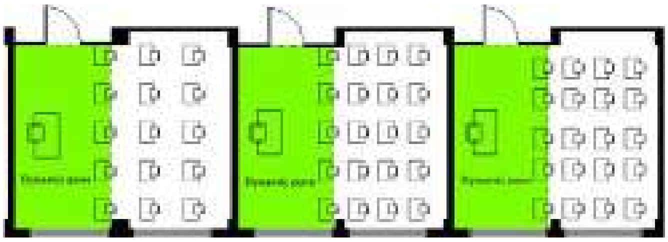

Fig. 8. *From left to right: scenario 1, scenario 2, and scenario 3.*

4.4.3. CLASSROOM: CHECK A.2.B

This check concerns the distance between the teachers' *rime buccali* and first-line pupils' *rime buccali*: such a minimum distance must equal 1.5 m (Tab. 1). The algorithm works similarly to Check A.2.a. First, a "Room" is created for the area under investigation in Revit. Hence, the script verifies whether the room complies with the minimum dimensions required. Results report negative outcomes for the typical classroom layout, which means that teachers are typically quite close to the first-line students. On the contrary, in the case of the modified layouts according to the safety guidelines, the distances are fully compliant with the safe use of the classroom.

4.4.4. CLASSROOM: CHECK A.3

The last check for the classrooms is carried out considering the size and area per person necessary to define the maximum number of users present simultaneously (room capacity) and ensure social distancing. The limit imposed by the guidelines, as reported in Table 1, considers the ratio between the room's net area and the area per person equal to a circle of radius 1m. In this case, the algorithm performs the calculation by returning the maximum number of students allowed to stay simultaneously in the classroom.

4.4.5. LABORATORY: CHECK B.1

Regarding laboratories, the guidelines identify the same rules for classrooms (Tab. 1). Therefore, the application of the scripts does not vary. In this case, the check is carried out on the typical laboratory layout. This check involves the verification of the minimum distance between scholars, which must be equal to 1 m (Tab. 1). Results show that some seats cannot be safely used as they do not comply with the rules on social distancing. As illustrated for the previous check A.1, the algorithm highlights in red color the stations to be kept free to meet guidelines requirements. As such, taking into consideration some fixed workstations, the ones marked as "empty" are eliminated, effectively halving the capacity of the laboratory.

Unlike classrooms, laboratories are usually organized with fixed workstations hosting, for example, instruments and computers whose position cannot be changed. Therefore, the verification is only carried out on the real laboratory layout without comparing it with redesigned layouts.

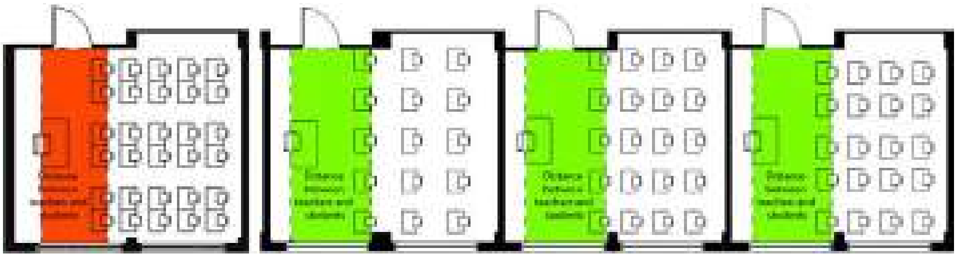

Fig. 9. *From left to right: typical classroom, scenario 1, scenario 2, and scenario 3.*

4.4.6. LABORATORY: CHECK B.2.A

The same verification of check A.2.a is applied here for the laboratories. As for the previous check B.1, the verification is only carried out on the real laboratory layout without comparing it with redesigned layouts. The dynamic area dimension is verified using the same methods of classrooms, and the checks carried out returned positive results.

4.4.7. LABORATORY: CHECK B.2.B

The last check for the laboratory concerns the distance between teachers' and scholars' *rime buccali*, which has to be not less than 1.5 m (Tab. 1). In this case, the Dynamo algorithm returned a negative result, which means that scholars are too close to each other. Layout checks are then carried out by halving the room capacity with empty workstations: in that case, the result is positive as the distance between the occupied stations has actually increased.

4.4.8. AUDITORIUM: CHECK C.1

In the case of the auditorium, we refer to the Ministerial Decree of 19/08/1996 as amended: «Approval of the technical fire prevention rule for the design, construction and operation of entertainment and public entertainment venues». This standard is applicable to premises open to the public for entertainment with a capacity exceeding 100 people or with a gross surface area exceeding 200 m^2. The auditorium under investigation falls into these shapes. According to the standard, there can be a maximum of 10 rows composed of a maximum of 16 seats. Seats must be spaced at least 0.8 m apart. They also must be at least 1.2 m away from the walls. If a distance of 1.1 m between rows is achievable, it is possible to consider 20 seats per row for a maximum of 15 rows. Finally, corridors with a minimum width of 1.2 m must be provided if seats are arranged in sectors. The seat width equals 0.5 m for seats with armrests and 0.45 m without. The checks are carried out taking into consideration that the distance necessary to guarantee a safety condition is equal to 1 m. The verification of the real condition considers two hypotheses:

- first scenario: a distance between rows of 0.8m is considered. In this case, the check shows a drastic reduction of the usable seats, equal to a quarter of the total;
- second scenario: In the second case, a distance of 1.1 m between the rows is considered.

The verification shows only a halving of the seats that can be used safely.

In the case of the auditorium, seats can generally be fixed or movable. In the case of movable seats, they can be reconfigured to comply with safety measures. In the case of fixed seats, the checks carried out can be used to indicate which one must be kept free for compliance with safety conditions.

4.4.9. STAFFROOM: CHECK D.1

In the case of the staffroom, the following real layout is used for verification. The check here shows the unusable workstations according to the safety rules (Tab. 1). The layout is therefore redesigned considering a distance of 1.15 between the stations. In this way, the verification of the new layout shows that all stations can be used respecting the social distance, as highlighted in the following figures.

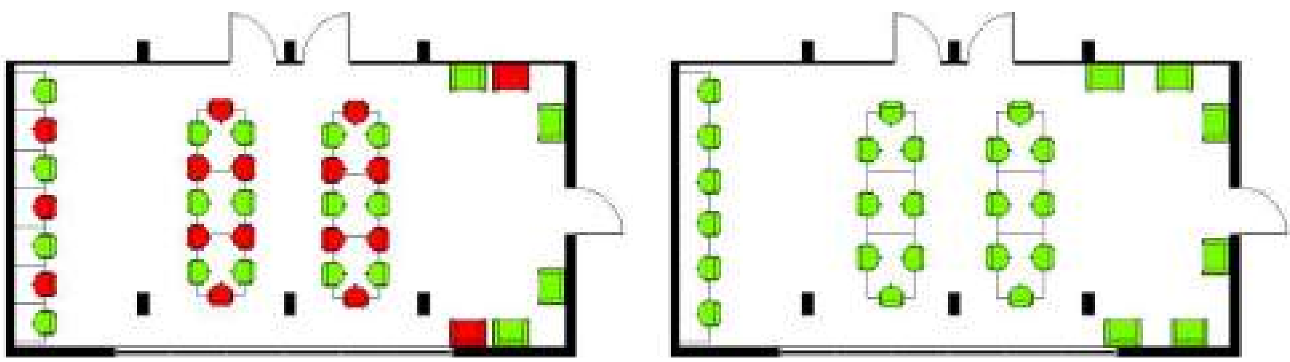

Fig. 10. *Staffroom. Check D.1. left: the unusable workstations according to the safety rules are shown in red colors; right: redesigned layout.*

4.4.10. CONNECTING SPACES: CHECK E.2

In this case, the dimension of all the school connective spaces is analyzed. In the case of corridors, the following condition must be respected: area per person > 1.25 m^2. By checking connecting spaces dimensions, it is possible to identify which can be used safely in two-way traffic and which must be necessarily used in one direction. The latter occurs in connection spaces with a high risk of gathering, as in the case of the entrance and exit from the school building. The checks applied to school building corridors under investigation report the following results:

- mezzanine floor: the stairs connecting the east area to the main atrium do not meet safety rules;
- first floor: the corridor of the southern classrooms and the corridor overlooked by the laboratories does not respect the safety rules;
- second floor: the corridor of the southern classrooms does not meet safety rules here, too.

4.4.11. GYM: CHECK F.3

The check identifies the gym's occupancy. For this kind of space, rules exclusively define a minimum social distance of 2 m. Here, the gym is modelled within Revit software, and the algorithm is then applied. The script calculates the number of students by defining a grid with dimensions of 2 m x 2 m. By using the script, results are shown in the room schedule or the properties set of the selected room in Revit software.

5. RESULTS AND DISCUSSION

Code-checking processes can be applied to various fields of construction engineering. Therefore, a BIM model can be used for compliance checks with different standards. The strength is to carry out checks automatically or semi-automatically with tools providing assurance of high-quality results. Conversely, by adopting the traditional method based on 2D CAD drawings, checks are carried out manually and on a sample basis. The literature clearly shows that manual approaches for building compliance checking usually lead to inconsistencies. Several tools capable of carrying out code-checking processes now exist, among which "Solibri" software is one of the most used [25]. Tools like "Solibri" are very useful, especially with reference to standard checks. Actually, some of these tools have several customizing options for rules. However, such tools do not have scripting capability. On the other hand, Visual Programming Language tools couple scripting capability to a rather easy user interface. Therefore, these allow for carrying out infinite applications, including modelling processes and code-checking processes with highly customized rules.

This paper shows the control rules scripting process to verify the BIM model compliance with the guidelines for contrasting the COVID-19 spread. This approach has never been considered so far. Therefore, the application of code-checking processes allows school environments to be tested in order to verify compliance with guidelines for fighting the virus spread. Moreover, standards are constantly evolving. Therefore, the proposed approach allows modifying the algorithm according to the evolution of the standards. The methodology proposed in this paper makes it possible to verify on a real-time basis all the school environments by returning their conformity or non-conformity status with standards.

The proposed case study is limited to the evaluation of some typical environments of the Michelangelo public school in Bari, Italy. In fact, the present paper does not intend to express a judgment on the conformity of the school building considered. The goal of the analysis is to propose a code-checking methodology for compliance with standards for preventing the virus spread. The approach presented here can be replicated in all school contexts and applicable to all BIM models. However, BIM models must be previously prepared for this kind of activity. Indeed, the proposed workflow cannot avoid the BIM model preparation phase. Designers defining building models that will be used for rule checking or other kinds of simulations must arrange them so that the models provide the information needed in a well-defined agreed framework. Hence, the application of the algorithms in a VPL environment can be implemented only when the model has been set. In order to ensure the scripts work properly without errors, the BIM model must have been enriched with the right semantic information. Current BIM platforms default to a minimal set of properties and provide the capability of extending the set. Nevertheless, users can add parameters to each relevant object to produce a certain type of simulation.

The approach proposed here, unlike manual controls, allows simultaneously processing a huge amount of data and simultaneously testing various environments. The BIM-based approach can be error-free and makes evaluations much faster. The lack of errors and the actions timeliness are essential parameters in emergency conditions. Thus, the design and construction managers are able to carry out several simulations to evaluate the optimal condition even before hypothesizing invasive re-functionalization scenarios both for the buildings and the human capital. The advantage is to manage several variables and apply them to different application scenarios, and this becomes essential in an emergency situation with few resources and time available. Furthermore, the visualization capacity of the result offered by BIM allows for increasing the space management's control capacity.

The standards of COVID-19 prevention are constantly evolving, but the paper is limited to the period of drafting the study. The present study intends to provide a methodology and not a regulatory framework to be adopted. Therefore, according to the authors, the most representative Italian guidelines are taken into consideration here, also studying the type of controls to be applied to school buildings. Although several studies investigate code-checking processes [21–23], applying the BIM-VPL approach to the fight against Coronavirus has never been considered.

6. CONCLUSION

The World has had to contend with a huge pandemic for the past two years. The COVID-19 spread has resulted in a number of catastrophic scenarios. To date, there are millions of confirmed cases and hundreds of thousands of deaths. With reference to the school system, a series of guidelines have been issued to continue using school buildings safely. In fact, e-learning methods are considered less effective, especially in social terms. The presented BIM-based approach allows the simultaneous verification of different school environments with respect to pre-established safety rules. The literature highlights several potential benefits of using automation to support design compliance checking. In this case, the use of VPL tools for code-checking processes allows the real-time comparison among different layout scenarios, helping decision-makers opt for the safest scenario and guarantee the greatest room capacity. This leads to better exploitation of school buildings without displacing students and teachers to other buildings or opting for e-learning solutions. Moreover, it has recently been shown that e-learning negatively affects the social relationships between scholars and school staff.

The present paper is the first approach of a broader research study. Then, the proposed framework should be evolved in the future. Further research will consider a greater number of national and international standards, and different case studies will also be deemed to consider other existing guidelines. Furthermore, future research will focus on working environments in general and not just school ones. Also, future works will consider the different restrictions that will be deemed to prevent pandemics like this. Indeed, although the World appears to be coming out of the pandemic condition, this approach could be used to counter another wave or different types of pandemics.

Authors contribution

C. Cavalliere: data curation, formal analysis, investigation, project administration, software, supervision, validation, visualization, writing. G.R. Dell'Osso: conceptualization, formal analysis, investigation, project administration, supervision, validation, writing. F. Iannone: formal analysis, investigation, project administration, supervision, validation, writing. V. Milizia: conceptualization, data curation, investigation, software, writing.

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