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The New Trend for A Sustainable Regeneration of Built Environment: Green Solutions and Digital Twin for Human Centres Design and Well-Being

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ABSTRACT

During the period when we were confined to our homes, engaging with family members around the clock and interacting with the world digitally while conducting remote work, numerous shortcomings in the architectural design of our buildings and indoor comfort levels became apparent. A significant issue highlighted by this experience was the lack of natural elements in living spaces, particularly the absence of green areas and vegetation, which are often considered exclusive features of luxury homes, offices, or villas. This paper explores how we focused on improving the ecological quality of building environments through a retrofitting project of existing office buildings in the historic city of Lucca, Tuscany. The eco-systemic design approach, pioneered by the Bexlab team at the University of Florence, not only supported and compared various retrofitting scenarios through digital twin simulations, but also emphasized the importance of integrating natural living spaces. This initiative aimed to foster a new connection between inhabitants, architecture, technology, and nature.

Keywords: architecture, digital, NBS, regeneration, sustainable

1. Introduction

Revitalizing Industrial Zones: Both a Challenge and an Opportunity

The environmental, energy, and aesthetic shortcomings of many existing buildings serve as a persistent reminder of the urgent need for architects to advance design practices towards sustainable regeneration. Among various urban landscapes, industrial areas exemplify the intricate challenges associated with ecological and energy regeneration in the built environment [1]. These zones, often situated on the borders of rural and natural landscapes, act as transition areas that have been characterized by outdated, uniform structures and infrastructure. Such areas often suffer from low environmental quality, which negatively impacts both the natural environment and the wellbeing of those living and working within them. The need for regeneration becomes even more pressing when we consider that these buildings typically host industrial processes that can be highly polluting and consume energy at a much higher rate than residential or commercial buildings.

As part of addressing these issues, the regeneration of these industrial zones becomes a key focus for reaching global sustainable development goals (SDGs). This is reflected in initiatives such as the European Union's Green Deal, which aims for climate neutrality by 2050. Within this framework, the Renovation Wave strategy has highlighted the need to enhance the energy efficiency of existing buildings. Furthermore, the New European Bauhaus initiative is redefining the approach to project development, emphasizing creativity and interdisciplinary methods to create inclusive, sustainable spaces, with a particular emphasis on merging beauty, culture, and environmental sustainability.

The concept of Eco-Industrial Parks (EIPs) has been in circulation since the 1990s, advocating for the sustainable development of industrial areas on a global scale [2]. However, despite the growing popularity of these parks, challenges such as greenwashing have often overshadowed genuine progress. Yet, EIPs have become a reality in many parts of the world, with numerous industrial sites now certified under leading sustainability rating systems such as BREEAM and LEED. However, when we turn our attention to Mediterranean regions, especially in Italy, few examples of truly sustainable industrial zones exist.

In Italy, despite national regulations such as the Ecologically Equipped Productive Areas (APEA) framework (Legislative Decree 112/98), a widespread culture of sustainability within industrial zones remains absent. Particularly, when these areas are situated between valuable natural landscapes and historically rich urban centers, the challenges are even more pronounced. In Tuscany, where the architecture competition discussed in this paper takes place, there has been a further regional effort to implement APEA guidelines, combining sustainable planning with green infrastructure designs to foster operational sustainability across these areas [3].

2. Method

This research aims to explore and develop sustainable design solutions for the regeneration of industrial environments through the use of digital technologies, specifically the application of digital twin and Building Information Modeling (BIM). The methodology applied in this study is an interdisciplinary design approach that integrates architectural, engineering, and environmental aspects, while using digital simulation tools to support decision-making in the design process.

Interdisciplinary Design Approach

To address the ambitious sustainability challenges, this research adopts an integrated design approach that brings together various disciplines. The team involved in the project includes architects, urban planners, landscape architects, structural engineers, energy engineers, and sustainability and safety consultants. Collaboration among these experts is driven by a shared commitment to sustainability principles, with the success of the project depending on the holistic integration of each expert's contribution.

Use of Digital Technology for Sustainable Design

The use of Building Information Modeling (BIM) and other digital tools is central to the design process. BIM is used to create a model of the building, encompassing its geometry, materials, and performance, enabling the simulation of various design scenarios predictively. This approach not only supports data-driven decision-making but also enhances collaboration across disciplines by enabling the sharing of a fully integrated digital model. Using simulation software, the design team can predict and optimize the building’s performance, especially in terms of energy efficiency and environmental impact reduction.

Environmental Performance Evaluation

This research evaluates the environmental performance of the proposed building design with a focus on energy efficiency, resource use, and ecological impact. The analysis considers bioclimatic and passive strategies, such as the use of sunlight, wind, water, and vegetation, as well as active technologies like photovoltaic panels and heat pumps. This evaluation also includes the use of renewable energy, rainwater management, and

microclimate enhancement, all of which aim to meet the Nearly Zero Energy Building (NZEB) goals and ensure long-term sustainability.

Ecological Approach and Nature Integration in Design

This design approach focuses on fostering a harmonious relationship between humans and nature. By utilizing nature-based solutions (NBS), the design seeks to re-naturalize urban spaces, improving human quality of life through interaction with natural elements. One of the primary objectives is to enhance ecological sustainability in urban areas heavily affected by pollution and industrial development, while also creating spaces that promote the well-being of their inhabitants.

Implementation of Digital Twin for Building Management and Performance Monitoring

Digital twin, or a virtual replica of the building, is used for real-time monitoring and management of the building's performance. Static technical data from the BIM model is combined with environmental data obtained from sensors at the building's site to assess the ecological impact and ongoing performance of the building. This approach allows for the optimization of building operations and demonstrates the benefits of green technologies, aiming to raise awareness of the importance of ecological solutions in living spaces.

Evaluation and Simulation Methods

Building performance simulations are conducted using software tools that support sustainability analysis, including simulations for daylighting and natural ventilation. For instance, natural daylight assessments of the entrance block of the building are performed using Sefaira-Sketchup software, which analyzes how summer and winter conditions affect natural lighting and building energy consumption (Figure 6). This analysis is crucial to ensure the design meets energy efficiency and occupant comfort goals.

3. Results and Discussion

A New Green Building in the Lucca Industrial District: The Architectural Competition

This paper presents the design journey of the award-winning project for a new sustainable building in the industrial district of Lucca, Tuscany, which emerged from an Italian architectural competition. The focus is on showcasing the design process as an exemplary model of green architecture, specifically tailored for Mediterranean industrial zones. This project aligns with the broader goals of Eco-Industrial Parks (EIPs) at local, national, and global levels.

The competition aimed to identify the best architectural solution for the headquarters of Sistema Ambiente Spa, a public company responsible for Urban Hygiene Services in Lucca (Figure 1). The project involves the extension of an existing building (approximately 4,400 m²) and the development of a 12,500 m² outdoor area. The site is designed to accommodate a diverse range of activities: administrative and technical functions, including public reception areas, office spaces, an auditorium, and a cafeteria, alongside technical facilities for waste management and maintenance of the company's vehicle fleet, which necessitate careful consideration of pollution control.

The competition established ambitious objectives, prioritizing a high-quality architectural redevelopment that emphasizes corporate identity, integration with the surrounding landscape, energy efficiency, and adherence to the Nearly Zero Energy Building (NZEB) standards. Additionally, the project emphasizes environmental quality through compliance with CAM (Minimum Environmental Criteria) and pre-certification using recognized sustainability protocols.

(a) **(b)**

Figure 1 Nature in the historical city-center of lucca (**a**) the renaissance and green city-walls; (**b**) torre guinigi (xiv century).

Behind the Award-Winning Project: The Integrated Design Approach

To tackle the significant challenges presented by the competition, it was essential to establish a unified cultural framework that could guide a collaborative and multidisciplinary design process. This involved the active participation of a diverse team, including architects, urban and landscape designers, structural and energy engineers, environmental experts, fire prevention and safety coordinators, geologists, and agronomists. The integration of these varied fields was made possible through the adoption of Building Information Modeling (BIM) and digital simulation tools from the project's outset. These technologies facilitated the creation of predictive design scenarios, enabling data-driven decision-making at every stage of the process [4] [5] [6].

The success of the project was driven by the collective commitment to sustainability, with each team member sharing a common dedication to proven principles that were continuously reviewed and refined throughout the design process. The team worked together to apply an ecological mindset that emphasized the harmonious co-evolution of the built environment with nature and humanity. In this context, the goal was not only to create a functional building but to activate positive, sustainable relationships between the architecture, the environment, and the people who would interact with it [7].

This vision became particularly significant in the context of regenerating industrial areas. Such areas, with their history of ecological degradation, posed particular challenges in terms of recovery and renewal. Consequently, the new building was designed as a regenerative ecosystem—a living entity with a sustainable metabolism that could foster meaningful connections with both the surrounding natural environment and the urban-industrial landscape of Lucca. The design aimed to revitalize the industrial district, transforming it into a more attractive and environmentally integrated part of the city.

Designing with Nature

The core concept of this project emphasizes the essential role of nature in promoting human health, comfort, well-being, and social connection. Nature is not only integrated as an environmental element but also as a powerful design tool, enhancing both the aesthetic and communicative quality of sustainability. This approach aligns with the values embedded in Mediterranean urban and architectural traditions, where the symbiotic relationship between nature and architecture has long been a guiding principle [8]. Figure 3 provides a visual representation of the new Sistema Ambiente headquarters, showcasing the design's integration of natural

elements in its public spaces, such as the entrance portico and internal courtyard, which emphasize the harmony between built and natural environments.

In recent years, the concept of nature-based solutions (NBS) has gained significant traction globally, leading to the re-naturalization of urban spaces and buildings [9]. These solutions represent a paradigm shift in architectural practice, one that moves beyond traditional methods and embraces the regenerative potential of nature to heal and enhance the built environment. Figure 2 illustrates the bioclimatic and passive strategies adopted within the project, highlighting both winter and summer scenarios for optimizing the building's environmental performance.

By fostering specific eco-systemic relationships unique to each site, regenerative design aims to create a harmonious co-evolution between the built and natural environments. This process facilitates a virtuous cycle where environmental sustainability directly contributes to improving human well-being, and vice versa. Figure 4 offers an aerial view of the new headquarters, reinforcing the project's ability to blend into its surrounding landscape, furthering its role in ecological restoration.

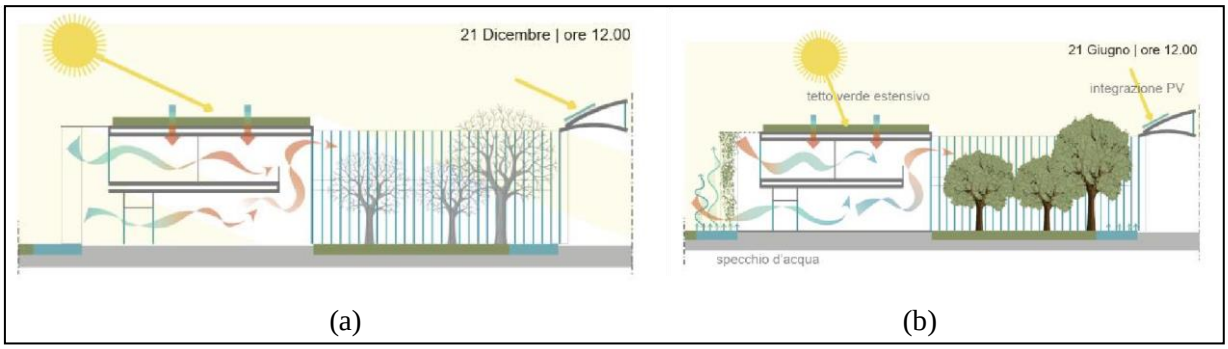

Figure 2 Scheme of the bioclimatic and passive strategies adopted within the project (**a**) winter scenario; (**b**) summer scenario

Figure 3 View of the new sistema ambiente headquarter (a) view on the entrance portico; (b) view on the internal courtyard

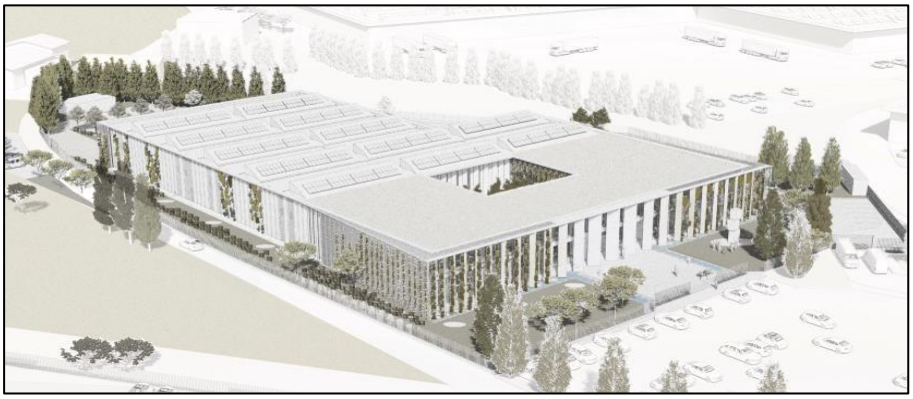

Figure 4 Aerial view on the new sistema ambiente headquarter.

Building upon the Mediterranean tradition of bioclimatic architecture, the project integrates natural elements—sun, wind, water, and greenery—as 'living building materials.' These resources are combined with both passive and active technological strategies to optimize environmental performance. Not only does this approach reduce energy consumption, minimize resource depletion, and mitigate pollution, but it also enhances biodiversity. Furthermore, by improving the microclimate, the design ensures that public and workspaces provide a high level of comfort, promoting both physical well-being and mental satisfaction. This synergy between nature and technology ultimately fosters spaces that are not only environmentally responsible but also enrich the human experience through their aesthetic appeal and sustainable functionality [8] [9].

Towards Zero Energy and Environmental Impacts

Guided by the principles of regenerative sustainability and Mediterranean bioclimatic design, the integrated approach of urban planning, landscape design, and architecture has significantly reduced the energy demand of the new Green Building. Passive design strategies make use of four primary natural resources—sun, wind, vegetation, and water—optimizing thermal gains in winter, maximizing insulation and thermal storage, and mitigating solar radiation. Additionally, natural ventilation, the reduction of the heat island effect, and the use of reflective surfaces in the summer are crucial for maintaining an energy-efficient environment.

Building on these advantages, the project adopts an energy strategy centered on electricity, avoiding fossil fuel-based energy sources. This includes the use of heat pumps powered by a photovoltaic system integrated into the sawtooth roof over the building’s technical area. The photovoltaic system directly harnesses solar energy, with annual production meeting the NZEB (Nearly Zero Energy Building) targets [10] [11] [12] [13]. Complementing this, three micro-wind turbines are strategically placed in the entrance square, further supporting renewable energy goals. Additionally, solar thermal panels are installed on the roof to provide hot water for sanitary purposes and assist in vehicle washing, also aiding the operation of the heat pump during the warmer months.

Water management is a key focus of the project, with multiple systems for water recovery and reuse. Rainwater is collected and separated based on its source. Rainwater from the green roof is filtered and drained through its layers, while runoff from other surfaces is directed to Sustainable Drainage Systems (SuDS) for mechanical and biological treatment. The treated water is then repurposed for irrigation, an external micro-nebulization system, and toilet flushing. Moreover, the vehicle washing system is designed to operate autonomously, with specific treatment processes for recovered water, though it connects to the primary rainwater collection system when necessary. To further support environmental stewardship, the project envisions creating an educational space that highlights sustainable practices and the role of waste management. This initiative aims to engage the public, providing an experiential learning environment that promotes awareness of contemporary environmental issues. Figure 5 provides a synthetic representation of the nature-based solutions adopted in the design, visually summarizing how these strategies contribute to the building's sustainability goals.

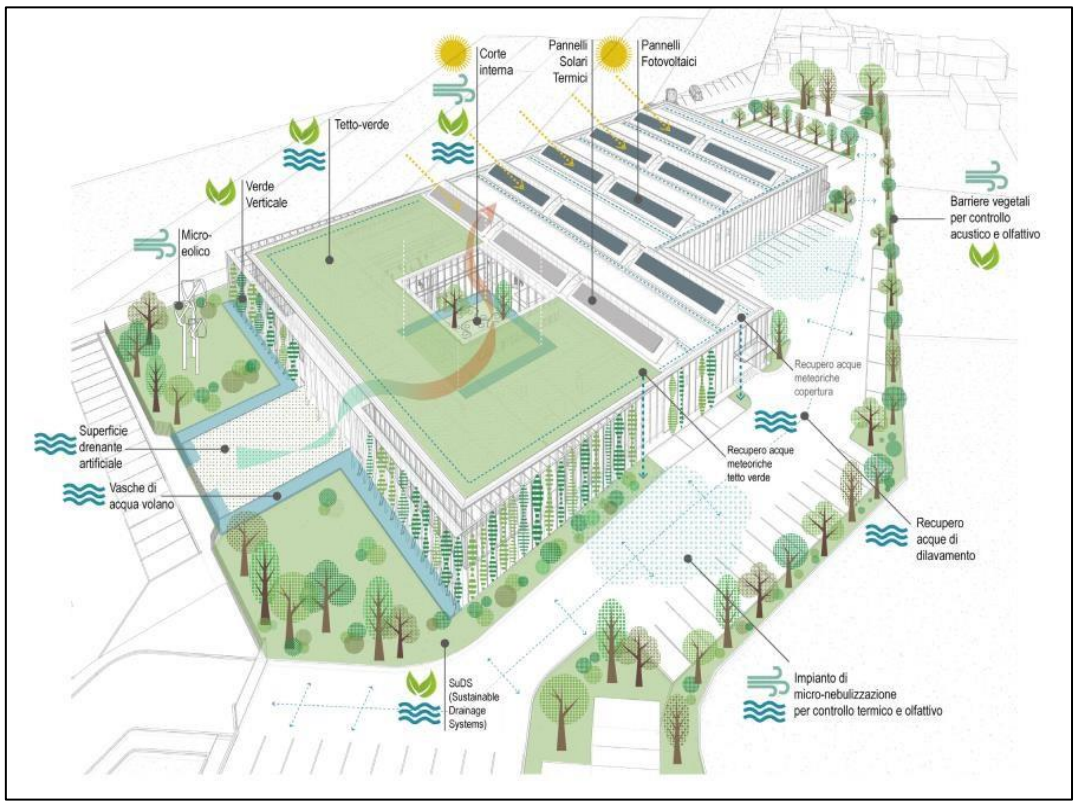

Figure 5 Synthetic representation of the nature-based solutions adopted

Communicating Innovation to Create Environmental Awareness

Enhancing the company's mission, the design process was integrated with a communication strategy that envisions the new building as both a model and a laboratory, designed to instigate a chain of values that raises awareness of environmental sustainability for current and future generations. The building serves as an icon of ecological design, a living manifesto of sustainable practices and responsible use of environmental resources. It provides a tangible example of the effectiveness of ecological choices, becoming a space for experimenting with educational paths, awareness-raising activities, and training initiatives on various environmental topics, with waste management being the starting point.

Addressing the ambitious sustainability challenges set forth by the competition, the integrated design mitigates the impact of the new building in its surrounding environment. Through green interventions, it reconciles the boundary between the urban/industrial landscape and the natural/rural landscape of the river and plain. At the same time, it contributes to global sustainability goals by promoting energy efficiency, reducing environmental impact, and improving the quality of public and workspaces. While the integration of nature into the built environment has long been recognized as beneficial for both people and the planet, doing so requires a deep understanding of interdisciplinary design processes [14] [15]. By embracing and innovating Mediterranean urban and architectural traditions, the project integrates natural elements with technological solutions. The adoption of validated digital tools and methodologies supports the design process, allowing for the demonstration of the positive impacts of natural elements on spaces and human well-being, as well as the building’s low environmental impact.

As evidenced by the winning design for the new headquarters of Sistema Ambiente Spa, ecological and digital transitions are mutually reinforcing. The digital domain enables data-rich, predictive co-design processes that support ambitious environmental and sustainability goals. The design process was significantly supported by a Building Information Modeling (BIM) model, which captured the geometry, materials, and performance data of the existing building. This model was continuously enhanced with green technologies and innovative project solutions. By utilizing simulation software that is interoperable with the BIM model, the design team optimized the workflow, integrating the contributions of various disciplinary teams. Figure 6 provides a natural daylight

assessment of the entrance block of the new headquarters, showcasing both summer and winter conditions. This analysis was performed using the Sefaira-Sketchup software by Trimble Navigation, and it demonstrates the building's ability to optimize natural light and energy efficiency throughout the year.

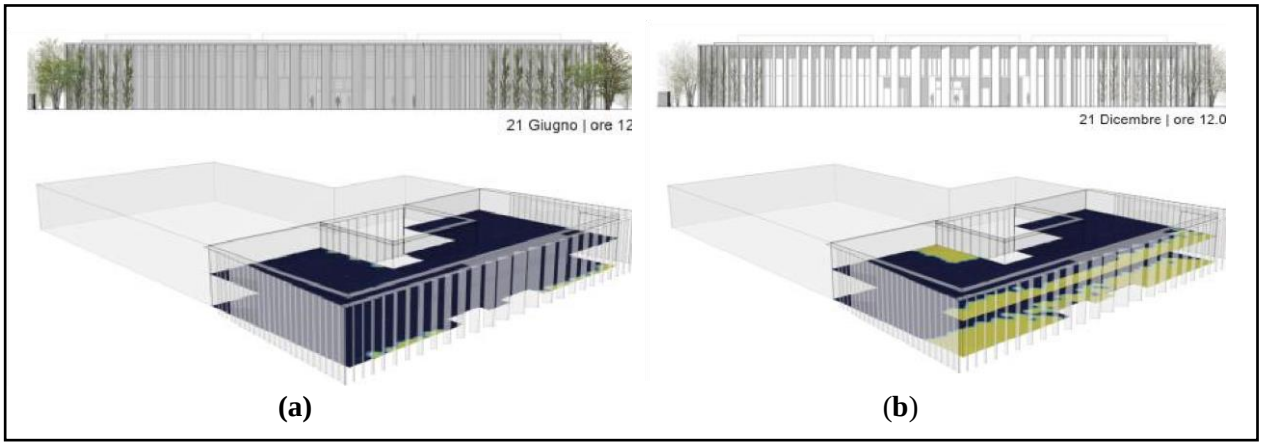

Figure 6. Natural daylight assessment of the entrance block of the new headquarter : (**a**) summer condition; (**b**) winter condition (performed with the software sefaira- sketchup by trimble navigation).

4. Conclusion

While the integration of nature into the built environment has long been recognized for its substantial benefits to both human well-being and the planet, it still requires careful consideration and active promotion within interdisciplinary co-design processes. By embracing and advancing Mediterranean traditions, the integration of nature-based solutions alongside technological innovations must be backed by reliable methodologies and tools. This ensures that the positive impacts of natural elements—such as their role in improving human health and reducing the ecological footprint of buildings—are fully understood and demonstrated. The successful design of the Green Headquarters exemplifies how green and digital transitions can be harmoniously combined. The use of digital technologies facilitates data-driven and predictive co-design processes, allowing for the exploration of more ambitious environmental and sustainability scenarios. Looking ahead, as outlined in the design proposal, it is crucial to further enhance the innovative aspects of the Green Building by incorporating Digital Twin technology. This virtual representation of the building can merge static data (from the BIM model) with real-time environmental data, collected by sensors embedded in both the building and the surrounding urban spaces. This integration with IoT systems allows the user experience to be considered, offering valuable insights into how green technologies impact both human and environmental outcomes. By making these benefits visible, we can raise awareness of the positive influence ecological solutions can have on living spaces.

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6. Conflict of Interest

The authors declare no conflict of interest in the preparation and submission of this manuscript. The research was conducted independently, and no financial, personal, or professional relationships could have influenced the content or outcomes presented in this paper. All collaborators involved in the study, including those from the University of Florence and the interdisciplinary design team, have contributed equally and transparently to the work. Furthermore, there was no involvement of any external commercial entities or organizations that could have had an undue influence on the study's findings or conclusions.

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