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SUSTAINABLE DEVELOPMENT

SOCIAL INNOVATION

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HEALTHCARE AND WELLNESS

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TECHNOLOGY APPLICATIONS

TREELOGY: Preserving Urban Forests through IoT Monitoring Data of Greenery

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Abstract

The aim of the paper is to explain the methodology and outcome of an R&D project involving designers, data scientists and botanists along committed in the field of Nature Based Solutions, with the goal of creating new systems (Cabinets) to monitor the health and stability of urban forests. They offer opportunities and risks related to the stability and development in anthropic environments. Therefore, a new interdisciplinary approach to managing and monitoring this emerging problem is essential. The Treelogy project represents an important step forward in this field through IoT multisensory systems that collect data in a cloud, allowing targeted mitigation and remediation choices to be made. Additive manufacturing methods are used to make monitoring system prototypes. It is therefore clear that the transdisciplinary approach of design, computer science and botany is essential for the development of new research processes aimed at solving complex problems.

Introduction

Urban forests play a crucial role in addressing challenges related to climate change within increasingly complex urban areas. In addition to creating connectivity between urbanized land, agricultural land and forest land, it is evident that trees have a mitigating function on urban air temperatures. The temperature difference between urban and suburban areas with forest cover show differences exceeding 10 C. This finding characterizes the urban heat island. As a consequence of thermal regulation by evapotranspiration, a tree, for each cubic meter of wood, can release about 150 cubic meters of water vapor into the atmosphere, contributing significantly to regulate temperatures in the microenvironment surrounding it (Daina, 2017). This reactive capacity is amplified by the tree density of urban forests, which also have a crucial impact in combating air pollution through the reduction of particulate matter (Salbitano, 2020).

To ensure the effectiveness of these responsive systems, it is necessary to carefully understand and monitor their health and stability through the collection and interpolation of a wide range of parameters related to plant physiology, environmental conditions and structural stability of elements integrated into the urban context. In 2018, the Italian Ministero dell'Ambiente e della tutela del Territorio e del Mare (currently the Ministry of Environment and Energy Security) through the Strategia Nazionale del Verde Urbano (National Urban Green Strategy) focused on the topic of environmental monitoring. Taking correct information on plant health status (biomonitoring) and monitoring environmental data on air quality are essential for the identification of urban and peri-urban soils where management intervention is a priority in order to improve the potential of tree systems in the phytoremediation (Atelli et al., 2018).

Data acquisition systems and their integration into widespread networks that enable the selection and diffusion of environmental information turn out to be an emerging aspect in the so-called Nature Based Solutions. This field explores new interaction forms between industrial design and socio-technical innovation processes, involving social communities, service systems and production, interconnected through IoT processes (Baek et al., 2018).

A critical perspective is able to recognize and avoid the risks of contemporary data-driven technologies by acting within the emerging processes of formalizing the digital collective (Tactical Technology Collective, 2017). Research has developed data-driven solutions that can help take in a critical mass of information that is also extremely useful for implementing environmental policies and building collective awareness of the effectiveness of urban forests in dealing with environmental problems and their maintenance status. In this context, it is possible to refer to codified processes of developing, producing and visualizing the communicative language of data, data set desk; data set field; data set full (Sicat et al., 2018). Within this perspective, the implementation of strategies involving the use of advanced IoT sensor systems is crucial for the sustainable and digital development of the urban environment. The design, management, and monitoring of urban forests is only possible through an interdisciplinary approach, where expertise in design, computer science, and botany converge.

This paper explores the interdisciplinary R&D project Treelogy and its impact in promoting advanced urban forest monitoring and management solutions that can address environmental challenges in future cities. It will also illustrate the design process of prototypes intended to specialized measurement cabinets, made through the use of additive manufacturing technologies.

Urban Forests

More than half of the world's population lives in urban areas and by 2030 one out of three people will live in a city with more than one million inhabitants (United Nations, 2016). Building resilience against urban stresses has become a major priority for both local governments and citizens. It is crucial to make Smart Cities healthy and attractive places for the long-term development of societies. Trees and forests in the rural-urban continuum can play a distinctive environmental, social and economic role. In this perspective, Urban Forests can offer a key tool for maintaining environmental balances and a wide range of benefits for the well-being of citizens (Figure 1). Interaction with nature has a positive impact on physiological functions and health, psychological and spiritual well-being and improved cognitive functions (Fuller et al., 2007).

Urban Forests represent an urban green infrastructure (UGI) that meets the need to preserve and continuously improve the environmental quality of cities (Pearlmutter et al., 2017). Trees act as environmental engineers, providing benefits that are indispensable to both human inhabitants and all other living organisms in the urban ecosystem. These benefits, known as ecosystem services, arise from the need to balance the impact of human activities on the environment and include moderation of microclimate and thermal stress, mitigation of air pollution, CO_2 capture, water regulation and purification, improvement of soil quality and biodiversity (Economy, 2014). The sustainable development of smart cities requires transdisciplinary strategies, ensuring collaboration among the various disciplines involved, such as urban planning, local economic development, design, botany, accompanied by the digitalization of forests. The implementation of cutting-edge technologies used for monitoring, acquisition and analysis in the field of Urban Forest research and development is necessary, as it enables detailed data on the health of the tree components of the urban ecological network, enabling cities to make thoughtful decisions and develop targeted strategies to ensure a healthy and sustainable urban environment. Technologies that can be used effectively to achieve these goals include the Internet of Things, wireless sensor networks and the Internet of Trees. (Singh et al., 2022)

The urban scenario represents an element of pressure on the health and stability of these interconnected ecosystems and added to this are the ongoing dynamics regarding climate change with the dramatic consequences that accompany it (Figure 2). The combination of these factors can lead to

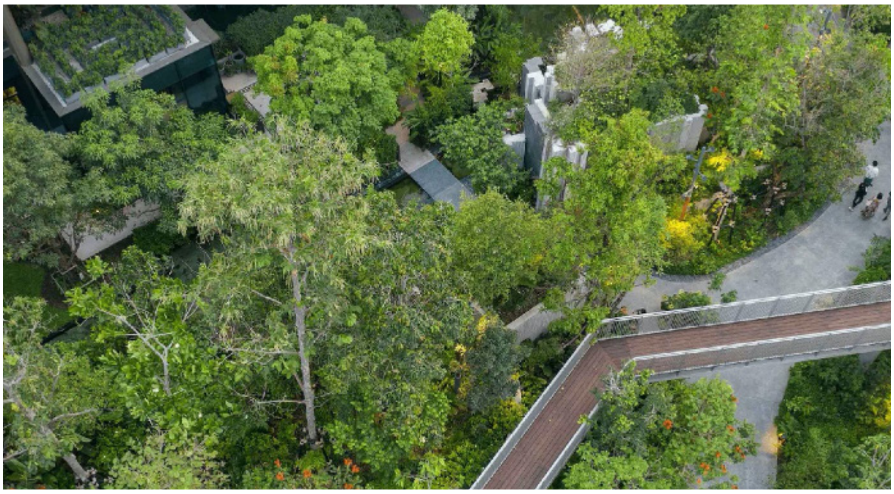


Figure 1. The Forestias project by Foster+Partners in Bangkok, 2016: Image by TK Studios on LandscapeArchitecture.

Figure 2. Bosco Verticale Project by Boeri Studio in Milan, 2014: Image by Boeri Studio on StefanoBoeriArchitetti.

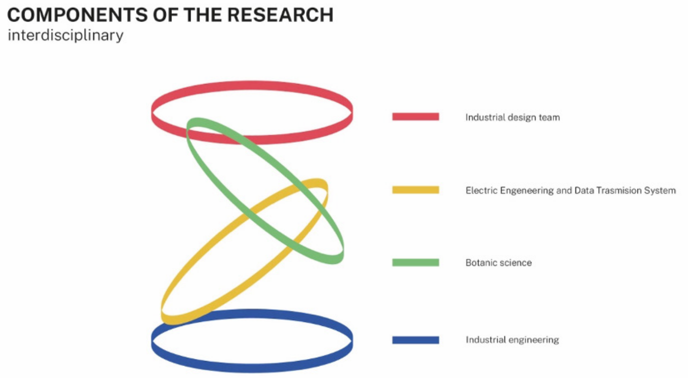
the deterioration of the health status of urban forests resulting in the loss of their ecosystem functionality (reduced provision of ecosystem services for the population) and increased risks related to the physical stability of structures (increased chances of tree collapses resulting in damage to people and property). It is therefore essential to work on projects that aim to integrate technological and advanced solutions through IoT and AI sensor systems in order to preserve and accurately manage Urban Forests.

Design-Driven approach

Within the project, design plays the crucial role of mediating and catalyzing between knowledge, activating interdisciplinary contributions, through a design-driven approach, such that design can be placed at the centre of the transition and innovation management process (Lotti, 2022). This approach embraces an iterative design cycle. Designers develop prototypes, gather feedback from users, make changes and iteratively refine the product or solution. This continuous cycle allows for dynamic adaptation to emerging needs. Another distinctive feature of this approach is interdisciplinary collaboration: design is able to involve professionals from different disciplines who collaborate together to ensure a comprehensive and integrated perspective during the development process.

This type of approach is effective in solving complex problems, implementing innovative solutions that go beyond the application of conventional methods, often introducing new patterns of thinking and creative approaches. By using a systemic approach where different disciplinary fields intersect, it is possible to develop a structured system that forms the basic methodology for implementing the design phases (Figure 3). It is a new design space, in which design methods can be profitably applied, through the participation and coordination of multidisciplinary project teams that work on system and product definition by working synergically on the physical and information planes, the forms of matter and data. In this way, the approach becomes organic, multidisciplinary and elastic, challenging classical design categorizations (Mincolelli, 2017). The design-driven approach, given its aptitude for solving complex problems, is particularly effective within a methodology aimed at fighting climate change and pursuing a sustainable, digital future. Constant reflections on Nature Based Solutions (NBS) and environmental monitoring through IoT demonstrate how design, as a process director, produces innovation by including within theoretical and scientific pathways hybridizations of available technologies, activating a

Figure 3. Multidisciplinary processing diagram by design team.



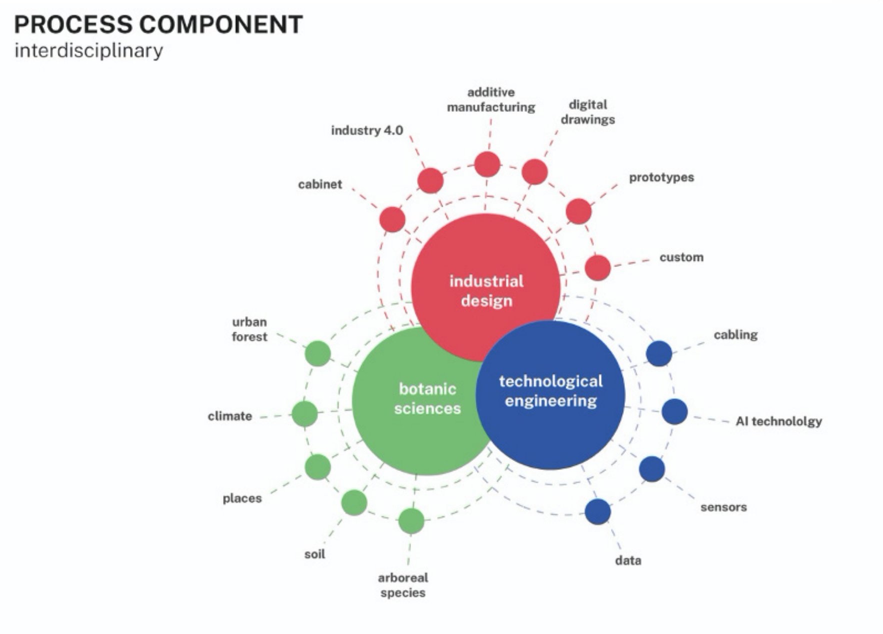


Figure 4. Components of the research diagram by design team.

system in which creativity, technology and multiple disciplines combine into a solution that is readily available (Figure 4). This concept is well summarized in the catalogue of Nature collaborations in design exhibition by Cooper-Hewitt Museum through the statement:

The approach is transdisciplinary and involve scientists, engineers, advocates for social environmental justice, artists, and philosophers, who apply their conjoined knowledge toward a more harmonious and regenerative future... The challenges to our planet today are so complex that they cannot be solved by one discipline. Design is the bridge. It translates scientific ideas and discoveries into re-la-world applications. (McQuaid, 2019, pp. 6-9)

The project

The main objective of the project is the implementation of IoT sensor systems that are useful for monitoring urban forests in order to obtain the necessary tools for proper and thoughtful management of greenery in urban context. Specifically, eco-physiological parameters, photosynthetic efficiency, evapotranspiration and water stress, carbon sequestration, biomass and woody growth and canopy health status of sample individuals of the urban forest were monitored, determining their health status and predicting the occurrence of systemic distress of the entire urban forest related to biotic agents such as fungal pathogens, pathogenic pests, and defoliating insect pulls, and abiotic agents such as drought, extreme or unseasonal thermal events and air pollution. Another key aspect relates to the stability of trees in urban settings, reporting in advance warning situations that in extreme weather events could lead to collapses that would undermine the safety of property and people. Particular attention is paid to capturing data on environmental safety and health levels related to air quality, airborne particulate matter and gaseous pollutants, extreme weather events, heat peaks in the summer season and the occurrence of forest fires.

These functional requirements are fulfilled by three different systems, each composed of multiple sensors, working in synchrony to provide an accurate picture of the health, efficiency and stability of urban forests. The idea is to design and implement systems that are as compact and manageable as possible for easy installation anywhere in urban forests.

Sensor systems, through IoT technology, communicate with each other and with a cloud. The collected data, through the use of AI, offer predictive

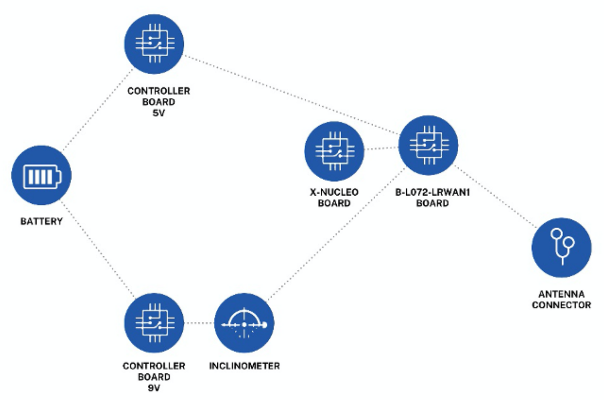


Figure 5. Node 1 stability diagram by design team

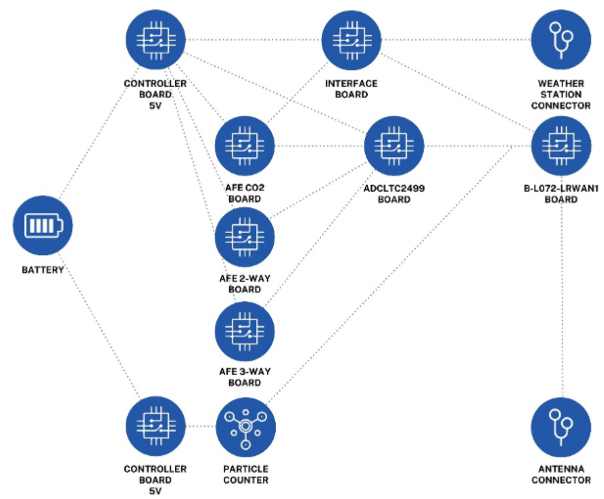


Figure 6. Node 2 physiology diagram by design team.

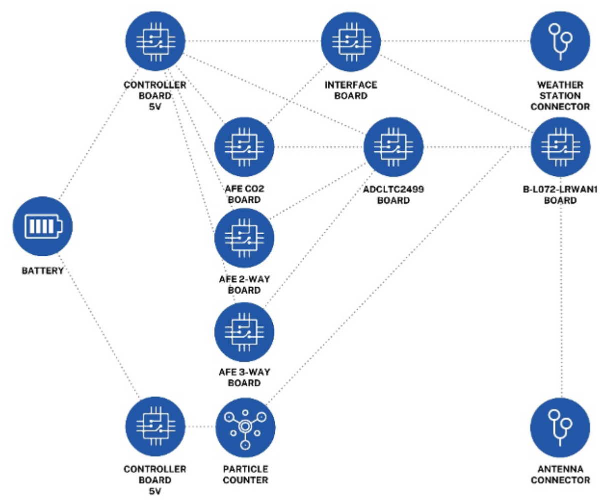


Figure 7. Node 3 environmental quality diagram by design team.

scenarios that provide the basis for making choices and performing specific mitigation and corrective actions. The design team specifically dealt with all phases of the design of the sensor systems, which consists of three main nodes, each dedicated to specific functionalities, defining: the stability node, the ecophysiology node and the environmental monitoring node. The first two nodes will be placed at a variable height along the tree trunk (stability and physiology), so as to directly monitor the status of the specific tree species (Figure 5 and 6). On the other hand, the last node is placed on a stand within the urban forest space to monitor its general condition related to environmental quality (Figure 7). This project was realized thanks to the collaboration between the design team of the University of Naples Federico II and the DST of the University of Sannio, for the botanical and Data Science components ensuring an integrated approach. Through the sharing of mechanical and functional specifications related to the various nodes, it was possible to optimize the study of the different components of these systems.

Methodology and Additive Manufacturing

The Cabinets are designed to monitor various ecophysiological, stability and environmental parameters within an urban and forest context. In this regard, the design team played a crucial role in conceiving the Cabinets and making the prototypes through the use of additive manufacturing technologies.

The use of additive manufacturing (AM) in creating sensor protection units dedicated to environmental monitoring represents an innovative and effective approach. Additive manufacturing, commonly known as 3D printing, offers a number of advantages that can be crucial in this specific context. One of the main advantages of AM is the speed of this technology. The speed advantage is not just about the time it takes to build parts. The acceleration of the entire product development process relies heavily on the use of computers through the smooth transition from 3D CAD to AM. Just as 3D CAD is becoming what you see is what you get, so is AM, and we could safely say that what you see is what you build (Gibson et al., 2021).

The key aspects that make this technology the most suitable solution for the realization of Treelogy Cabinets are primarily derived from personalization and optimization. Additive manufacturing allows the creation of highly customized control units tailored to the specific installation needs and surrounding environmental characteristics (Figure 8). This design flexibility enables the optimization of control units to enhance sensor accuracy and ensure greater resistance to adverse environmental conditions. 3D printing also enables the production of components with high geometric complexity, facilitating the integration of multiple sensors and protective devices into a single unit (Figure 9). This approach allows for increased functionality in a limited space, improving the overall efficiency of the Cabinets. In addition to these principles, additive manufacturing offers the possibility of using advanced materials, such as specialized polymers or weather-resistant additives. The targeted selection of materials contributes to ensuring the long-term durability of the product, especially considering continuous exposure to external agents. 3D printing enables more efficient production, reducing production times compared to traditional methods. This not only contributes to the rapid implementation of control units but can also reduce pro-

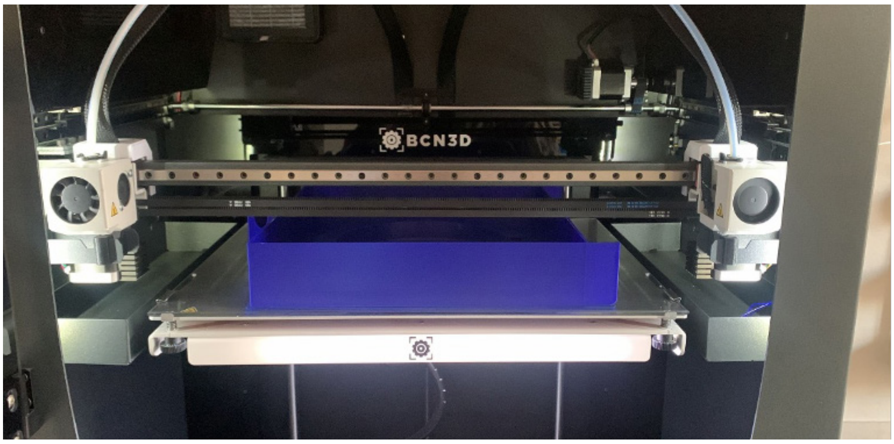


Figure 8. 3D printing phase of the cabinet prototype: Photo by design team.

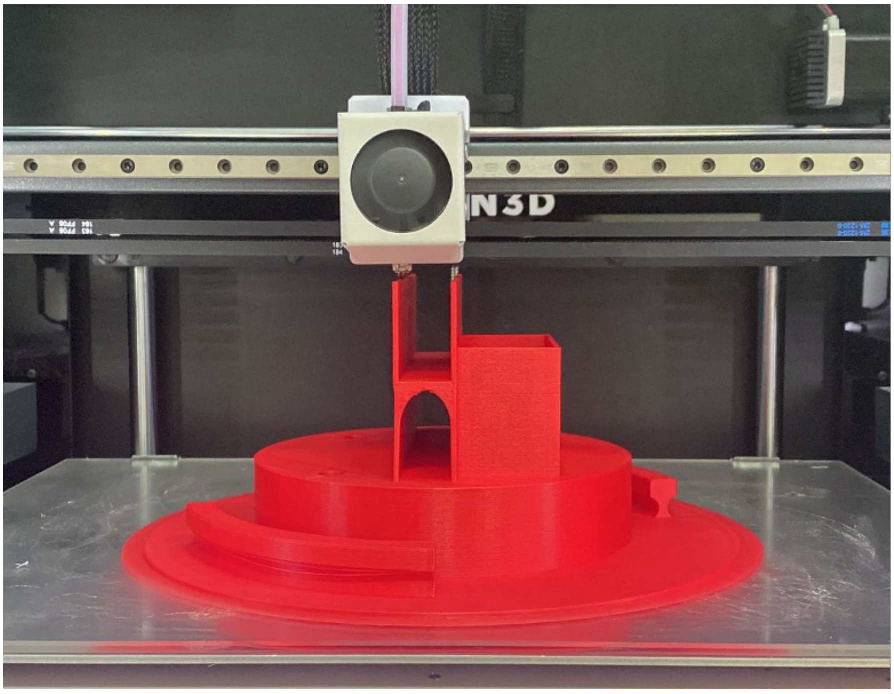


Figure 9. 3D printing phase of the cabinet prototype: Photo by design team.

duction costs, especially in small-scale production or prototyping scenarios.

The flexible nature of additive manufacturing allows easy adaptability of control units in response to technological advancements or changing environmental needs. The ability to make changes quickly and cost-effectively ensures that control units remain at the forefront in terms of functionality and performance. Some additive manufacturing techniques allow the use of recyclable materials, reducing the overall environmental impact of the production process. The application of additive manufacturing in creating protection units for dedicated environmental monitoring sensors offers a flexible, efficient and highly customizable approach, contributing to improving the reliability and effectiveness of monitoring systems.

Process

The methodology of the project involves the division of work into phases, one propaedeutic to the other. All phases of the project process leading to the realisation of the cabinets will be described in detail. The phases include:

needs analysis, conceptual design, detailed design, simulation and virtual testing, assembly and integration and prototypes testing.

6.1 Needs analysis

The needs analysis was essential to fully understand the requirements of each of the three monitoring system: ecophysiology, stability and environmental monitoring. This approach allowed a complete and integrated view of the needs of the system. A detailed analysis of the parameters to be monitored was carried out. The variables studied concerned plant ecophysiology, soil or structural stability indicators, as well as environmental parameters such as temperature, humidity and other relevant factors. Identifying these parameters was crucial to guarantee that the monitoring systems were able to capture and record all the information necessary to monitor and control the system. Subsequently, the environmental conditions in which the cabinets are to be located were examined. Factors such as exposure to sunlight, the presence of atmospheric agents, ambient temperature and other elements that could influence the performance of the system were evaluated.

Conceptual Design

The conceptual design for the cabinets involved several key aspects, considering the specifications gathered during the needs analysis phase.

The dimensions of the cabinets were considered to guarantee that they would be adequate to accommodate the sensor systems used by the project. The internal layout was, therefore, designed to maximise space efficiency, while providing easy accessibility for maintenance and monitoring. The fixing systems were chosen from those most suitable for mounting the control units on the trunk of the trees and on supports (poles) fixed to the ground. The design team provided a system with slots on the back of the cabinets to anchor the prototypes directly to the trunk by means of sturdy straps, with the possibility of choosing the most suitable height for the different situations to be monitored (Figure 10).

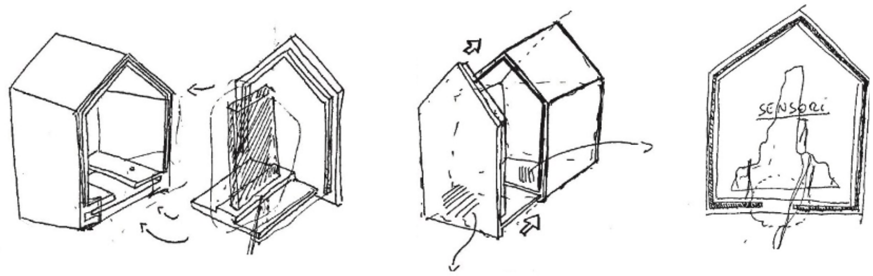


Figure 10. Conceptual design sketches by design team.

The choice of materials took into account the need to resist the adverse environmental conditions. Therefore, materials resistant to corrosion, various atmospheric conditions and deterioration caused by UV radiation were selected to guarantee a long-life cycle. The materials chosen are compatible with additive manufacturing technology. The cabinets were designed with the intention of encouraging environmental integration. The design concept aims therefore to simulate existing bird house with a typical sloping roof shape, in order to avoid accumulation of water and other materials. The use of bright colours for the cabinets (red and blue) not only provides a visually appealing appearance, but also serves functional purposes; it can provide, for example, clear visual indications of the specific function of the cabinets (Figure 11).

Overall, the conceptual design aims to guarantee that the cabinets not only fulfill strict technical and functional specifications, but are also harmoniously integrated into the environment, paying attention to both functionality and aesthetics.

Detailed Design

The technical details of the cabinets were developed considering the cable access arrangement, ventilation, sensor openings, security locks and hermetic closure systems to prevent water and dust infiltration. The most appropriate solution was the construction of a fixed body and a central core (Figure 12) with a circular base that fits inside it by a bayonet joint at the bottom of the cabinet. In this way, all sensors are assembled on the central core

Figure 11. Project render by design team.

and can be easily removed for maintenance by rotating the bayonet joint. In addition to being functional for mounting the sensors inside the cabinet, this solution is also functional for preventing water and dust infiltration, as the joint is located at the bottom.

The detailed design phase involved the in-depth development of the technical aspects and details of the cabinets, with the aim of guaranteeing optimal system operation and a long-life service. Particular attention was paid to the arrangement of the cabling entrances to simplify installation and maintenance and to reduce the risk of damage to the feed-through cables. The chosen solution also includes an efficient ventilation system, which is necessary to prevent overheating of the technological components and its stable operation. In addition to the openings for ventilation, openings were provided for the sensors, in order to maximise the efficiency in the measurement of the different parameters and guarantee the necessary exposure of the environmental sensors.

During the design process, the design team took into account the security of the system, providing strong security locks to protect against unauthorised access and hermetic sealing systems to prevent water and dust infiltration, thus ensuring adequate environmental protection for the internal components.

Simulations and virtual tests

During the post-development process, extensive simulations and virtual tests were conducted in order to evaluate the effectiveness of the Cabinet design in a variety of environmental scenarios. This approach aims to guarantee that the Cabinets can successfully withstand adverse conditions such as torrential rain, high temperatures and strong winds and maintain their performance reliably over time.

The results of the simulations and virtual tests provided valuable data to further optimise the design through changes in the shape of the body and the need to insert structural reinforcements to prevent the central core from breaking. This enabled the design of the cabinets to be optimised before production, reducing post-production modifications and, consequently, costs.

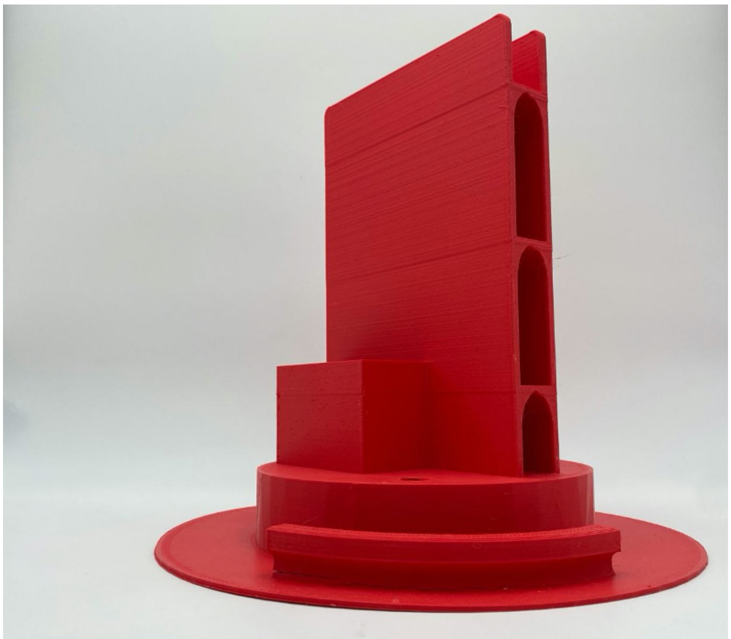
Assembly and integration

The different components were produced through additive manufacturing technology. After assembling the sensor systems and the subsequent cabling on the central core, special attention was paid to the assembly of the core with the outer body in order to ensure the safety of the system. The missing parts were subsequently integrated, i.e. locking systems, safety locks, cooling fans and cable guides.

6.6 Prototypes testing

The prototype cabinets were subjected to extensive testing in the laboratory by simulating real conditions and directly in the field, in the places where they will later be installed. The tests carried out verified the functionality, the correct functioning of the sensors, data management, connectivity and, more in general, the compatibility of the system. Strength tests were also carried out to assess the structural robustness of the cabinets in response to mechanical stress. These tests guaranteed that the system could withstand external stress without significant damage. During the testing, detailed data was collected on the performance of the prototypes. These data are then analysed to identify any anomalies or improvements needed.

Figure 12. 3D prototype of the central node: Photo by design team.



During the various design phases, the design was continuously optimised. Additive manufacturing made possible numerous tests, producing scale prototypes and testing the possibilities of assembling cabinet components and sensor technology within the cabinet. The interdisciplinary approach allowed a continuous exchange with teams of data and computer scientists who directly assembled and tested the cabinets. In this way, the design team was able to obtain step-by-step feedback in order to optimise the product realised in the best possible way to make it as functional as possible with respect to the set objective.

Expected results

The project aimed to develop IoT sensor systems for monitoring urban forests, in order to provide essential tools for wise and accurate management of green areas in urban context. Expected results include the ability to collect continuous data on key eco-physiological parameters, such as photosynthetic efficiency, evapotranspiration, water stress, carbon sequestration, biomass and woody growth, as well as assessing the health of tree crowns. These systems would allow preventive evaluation of potential systemic threats to urban forest health, arising from biotic agents such as pathogenic pests and insect infestations, as well as abiotic factors such as drought, extreme heat events and air pollution. The implementation of such advanced tools will contribute significantly to the sustainable and careful management of urban green areas, promoting the conservation of biodiversity and improving the quality of life in urban centres.

Conclusion

The Treelogy project is a NBS example of the contribution given by urban forests and the need for integration with the dimension of data generation and dissemination, specific to smart cities. The project develops a projection in the methodological ambit of interdisciplinary design-driven processes in areas of environmental action in urban forests. In this specific example, design has worked in connection with disciplines such as botany and data science, coordinating the development of complex systems related to human interactions with the environment in its physical and digital dimensions. The design team was involved in product design, as well as digital representation and interfacing with digital manufacturing processes, together with data visualisation through the aspects of infographics. In particular, Cabinet systems were designed, capable of housing collecting cells and sending data. In the production of the systems, additive manufacturing processes were adopted allowing the production of scale prototypes and testing the possibilities of assembling cabinet components and the sensors within them.

At the same time, in facilitating the diffusion of data, risks due to forms of techno-solutionism were faced, acting within the emerging processes of formalising digital democracies that, through of specific operational tools, allow the widespread diffusion of environmental monitoring data.

Acknowledgments

Although this paper is the result of co-authors' combined work, it is specified that Mariarita Gagliardi drafted paragraphs 2-4, Silvana Donatiello drafted paragraphs 3-5, while Alfonso Morone drafted paragraph 6. Introduction and conclusion are attributable to all the authors.

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