Achieving SDGs in Industry 4.0. Between Performance-Oriented Digital Design and Circular Economy

Alessandra Battisti and Livia Calcagni

Abstract Design sits prominently at the heart of the circular economy and requires us to rethink everything: from products, to business models and cities. Since everything that surrounds us has been designed by someone—the clothes we wear, the buildings we live in, even the way we get our food—and mostly according to the linear model, almost everything needs to be redesigned in accordance with the principles of the circular economy. Circular design process comprises human-centred and performance-oriented approaches. Extending the life of a product allows it to remain in use for as long as possible, and may involve designing products to be physically durable or require innovative approaches that allow the product to adapt to a user's changing needs as time passes. Digital Design plays a crucial role in achieving quickly and efficiently, quality architectural projects both from the users' point of view and from a global perspective as it closes the loop of material flows.

Keywords Performance e oriented · Digital design · Circular economy · Architecture 4.0

United Nations' Sustainable Development Goals 11. Make cities inclusive, safe, resilient and sustainable · 12. Ensure sustainable consumption and production patterns · 13. Take urgent action to combat climate change and its impacts

1 Introduction

The digital revolution has set many challenges and opportunities before the architecture, energy and construction sector. Indeed the adoption of Industry 4.0 (I4.0) technology in sustainable production and circular economy has deeply transformed

A. Battisti (✉) · L. Calcagni
Dipartimento di Pianificazione, Design e Tecnologia Dell'Architettura, Sapienza Università di Roma, 00196 Rome, RM, Italy
e-mail: alessandra.battisti@uniroma1.it

L. Calcagni
e-mail: livia.calcagni@uniroma1.it

M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_2

the system of project design, construction, building management and maintenance, and last but not least, the sharing of information. I4.0, digitization, smart building, augmented reality have become part of the evolved common vocabulary of design in the construction sector and in particular in all its different declinations related to circular economy. The very concept of circular economy is amplified by I4.0, that provides a strong support to the different project phases, thanks to the integrated approach that allows to evaluate in a virtual way—and in advance—all the information related to the entire life cycle of a project: from design, to construction, demolition and disposal. The concept of circular economy from the perspective of performance-oriented digital design has gained momentum among businesses, policy-makers and researchers due to its potential to contribute to sustainable development [1, 2] through a series of efficiency and productivity improvements, commonly known as circular strategies. The high value of digitally oriented design is also emphasized in some EU technical-analytical reports [3] that highlight how standardized information management can contribute to the prediction of environmental performances and thus improve decision-making concerning the future impact of a project. This is achieved by detailing the various activities and respective indicators that characterize the project from construction in terms of climate-altering emissions, resource consumption and waste production, to construction in terms of transport, construction site, realization, and eventually to operation in terms of operating energy consumption, heating/cooling, shading, ventilation, water and waste treatment, building life cycle, use and maintenance. Innovative technologies and paradigm shifts applied to digitized design contribute to extend the useful life of building artifacts, to reduce waste, to discretize performance and improve environmental impact, to identify opportunities to reuse building materials and/or components. The knowledge of physical-technical-performance characteristics, the availability of materials, and the configuration of optimized combinations of materials and components, as well as the use of a standardized language that ensures and/or increases interoperability between different technical formats, also contribute to better planning and organization of resources. In this sense, digital technologies play a crucial role in improving circular economy strategies and practices by overcoming environmental problems and fostering paradigmatic approaches towards the achievement of the SDGs.

2 Methodology

The authors carried out an analysis based on performance-oriented digital design and on 7 strategies of the circular economy—recover, recycle, reuse, regenerate, repurpose, reduce, rethink—to assess how and to what extent the achievement of the SDGs can be found in some projects and in particular goals 12 (Responsible Consumption and Production: Reversing current consumption trends and promoting a more sustainable future) and 13 (Climate Action: Regulating and reducing emissions and promoting renewable energy). At the very moment, recovery and recycling actions carried out in construction processes do not always necessarily promote a circular economy, even though they are among the most common applied strategies in the construction field to date. It is precisely in the medium- and long-term planning on recovery and recycling that I4.0 could enhance the circular economy and lead to the pursuit, albeit partial, of these two SDGs. In relation to these, the essay reviews experimental digital tools and practices, showing how they can reduce waste, increase energy and ecological efficiency, effectively and efficiently employ renewable energies, close production cycles and maximize the preservation of the economic value of materials and products. The proposed methodology follows that used by Bocken [4], which identifies three iterative steps for a practice and literature review: (1) identification of topics and categorizations by literature review, (2) synthesis through the development of an integrative framework, and (3) identification and mapping of practical examples to validate and further develop the framework. The logical framework is essential to extend the knowledge base by providing a detailed review of Industry 4.0 between sustainable production and circular economy by integrating three contemporary concepts in the context of supply chain management: Agile approach; IIoT stack and Technology ecosystems.

Agile approach. An approach that employs rapid iterations, fast failures and continuous learning. An approach whereby research teams work together extremely effectively by facilitating collaboration between different functions and turning use cases into self-learning examples that enable rapid innovation and renewal.

IIoT stack. Smart manufacturing system that enables seamless integration of legacy and new Industrial IoT infrastructures to build a stable and flexible technological backbone through intelligent use of existing systems with efficient integration within a new technological smart manufacturing process while limiting costs, consumption and waste.

Technology ecosystems. Technology ecosystems with access to vast datasets and co-innovation opportunities that enable collaboration between technology vendors, suppliers, customers and related industries to implement cutting-edge solutions and best practices.

3 Limitations and Implications of the Research

One must keep in mind that digital transformations are revolutionizing all aspects of production, affecting not only processes and productivity but also people. The right applications of performance-oriented digital design technologies can lead to more effective decision-making, new opportunities for upgrading, retraining and cross-functional collaboration.

In the construction field, the impacts can be identified especially in the reduction of production time, optimized process management with win-win benefits associated with reduced environmental impact, made possible by lower emissions and reduced waste, and more efficient consumption of energy, water and raw materials. Yet, evident risks remain: by pursuing digital transformation as a theoretical exercise, many research centers unwittingly create isolated and local operations which have little to do with future cycles of manufacturing excellence. They fail to access a broader network of production as they are more technology-driven rather than value-driven This results in a technology-first rollout where proposed solutions are deployed without a clear link to real value opportunities, business challenges or market capacity to absorb them. In fact, a large majority of the experiments deployed remain at the pilot project level, as they don't develop the full potential of transformation through performance-oriented digital design also in terms of return on investment.

With so much at stake, manufacturers are investing a lot of time and money in digital transformation. These investments are paying off for some, but most are unable to scale successful pilot programs or take full advantage of new tools and technology to see significant returns.

4 Case Studies

Given the emerging and widespread amount of applied and realized projects, our study investigated not only academic sources but also practice case study examples and grey literature [5]. As mentioned previously, the identified framework embraces circular economy (CE) and industry 4.0 (I4.0) paradigms, digital fabrication (DF) processes and digital technologies (DTs), and performance oriented design (POD), all with a view to sustainable environmental design. The integrative synthesis was followed by the identification and mapping of practical examples to validate and further develop the framework. Indeed, there are some paradigmatic European and international examples that provide evidence of how the integration of performance-oriented digital design and circular economy principles and strategies is increasingly implemented in the construction industry for the achievement of the SDGs, in particular goal 12 and 13. In analyzing these virtuous case studies we asked ourselves why they work, in which terms they contribute to achieving the 7 strategies of circular economy: recover, recycle, repurpose, re-use, regenerate, reduce, rethink; and eventually to what extent the three concepts of supply chain management occur in terms of agile approach, IoT stack and technology ecosystems.

More precisely the case study research method involved a cross-case analysis following the presentation of separate single-case studies [6]. The case studies have been selected according to their relevance to the criteria and topics mentioned above and have been analyzed on the base of the same indicators.

4.1 Maison Fibre

Maison Fibre (Fig. 1), exhibited at La Biennale di Venezia 2021, is the result of research on robotically manufactured fibre composite structures carried out by the Institute for Computational Design and Construction and the Institute of Building

Structures and Structural Design at the University of Stuttgart. It is a full-scale inhabitable hybrid structure combining laminated veneer lumber with fibre-polymer composites (FPC). It is the first multi-storey building system fabricated with this novel technique [7]. In terms of tectonics the entire structure consists exclusively of so-called fibre rovings: bundles of endless, unidirectional fibres made of glass and carbon.

IIoT stack. The manufacturing process involves the use of a coreless robotic winding process, which allows for locally load-adapted design and alignment of the fibres. Coreless filament winding is a robotic fabrication technique in which conventional filament winding is modified to reduce the core material to its minimum, thus enabling an extraordinary lightweight construction [7]. This technological smart manufacturing process allows to limit costs, consumption and waste.

Technology ecosystems. This structure marks a turning point in the transition from pre-digital, material-intensive construction that makes use of heavy, isotropic building materials such as concrete, stone, and steel—which are often extracted in distant places, processed into building components, and carried over long distances—to genuinely DFTs with locally differentiated and locally manufactured structures made of highly anisotropic materials [8].

Agile approach. The extremely low material consumption combined with the very compact, robotic production unit allow to run the entire production on-site without a significant amount of noise or waste, both during the initial construction process, and during expansion or conversions.

Furthermore, this novel material culture in architecture brings about its entailed ecological (material and energy), economic (value chains and knowledge production), technical (digital technologies and robotics), and sociocultural matters.

4.2 Aguahoja I

Oxman's study focused on water-based robotic fabrication as a design approach and on enabling technology for additive manufacturing (AM) of biodegradable hydrogel composites meant for manufacturing architectural-scale biodegradable systems [9].

Technology ecosystems. The research group aimed at applying material ecology (ME) research to the study and design of a new biocompatible material for architecture, characterized by a programmed life, therefore bound to be gradually reabsorbed into nature [10].

IIoT stack. The structure (Fig. 2) is digitally designed and robotically fabricated: 3D printed from biodegradable polymers. The construction process involves a robotically controlled arm and multi-chamber extrusion system designed to mix, process and deposit biodegradable-composite objects combining natural hydrogels (e.g. chitosan, sodium alginate) with other organic aggregates. More specifically, the architectural skin-and-shell is made of 5,740 fallen leaves, 6,500 apple skins and 3,135 shrimp shells, 3D printed by a robot, modelled by water and coloured with

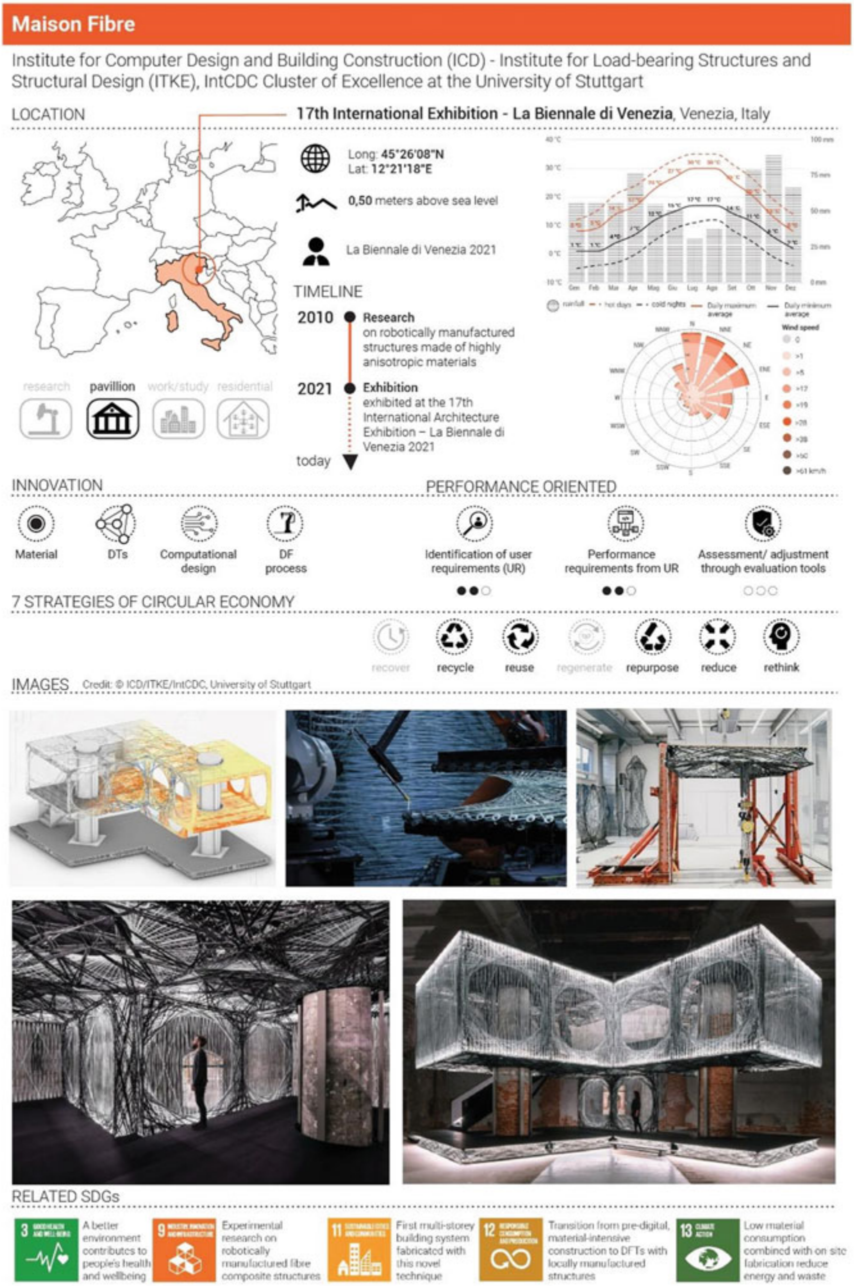

Fig. 1 Maison fiber case study resume form

natural pigments. The result is an organism-matter that captures carbon dioxide, enhances pollination, increases soil microorganisms and provides nutrients.

Agile approach. These water shaped skin-like structures are designed and manufactured as if they were grown, therefore no assembly is required as well as no disposal issues occur.

Despite the urgent need for alternatives to fuel-based products and in spite of the exceptional mechanical properties, availability, and biodegradability associated with water-based natural polymers, AM of regenerated biomaterials is still in its early stage [9]. Moreover, these structures react to their environment, adapting their geometry, mechanical behaviour and colour in response to fluctuations in heat, humidity, and sunlight (time-based 'temporal' behaviour). This structure shows how ME presents new opportunities for design and construction that are inspired, informed, and engineered by, for, and with nature. An architecture capable of programmatically decomposing could introduce a new type of disposal in the construction sector that does not alter the ecosystem, and is perfectly in line with life cycle assessment principles oriented to the cradle to cradle design.

4.3 Harvard Science and Engineering Complex

The new Harvard University complex (Fig. 3) is designed to inspire learning and scientific discovery while showcasing sustainability. Thus, special emphasis was set on effective façade design, efficient energy performance as well as occupant comfort. These are mainly addressed through the stainless-steel screen envelope which is designed according to parametric simulations and using a novel manufacturing method, hydroforming [11]. Hydroforming is an industrial cold forming process in which a metal blank is driven into a single mold with hydraulic pressure to form extremely thin parts with exceptional structural stiffness. It has been developed in the automotive and aerospace industries where weight to strength ratio has a compound effect on production cost, safety, performance, and energy consumption, but it has not been widely used for architectural applications yet [12].

IIoT stack. In this case hydroforming was applied in a sun shading system that leverages the advantages of this technology: lower tooling costs, precise geometric definition, and superior structural properties. Calibrated to the extreme seasonal variations of the local climate, the system is precisely designed and dimensioned to temper solar heat gain in the summer while maximizing daylight and solar energy in the winter, reducing cooling and heating loads [12]. The screen also reflects daylight towards the interior while maintaining large view apertures.

Agile approach. The use of parametric performance studies and simulations, including rapid prototypes, full-scale visual and performance mock-ups, and advanced industrial design and simulation software (like CATIA), allows to maximise structural, material and manufacturing efficiency and at the same time enables rapid iterations, fast failures and continuous learning.

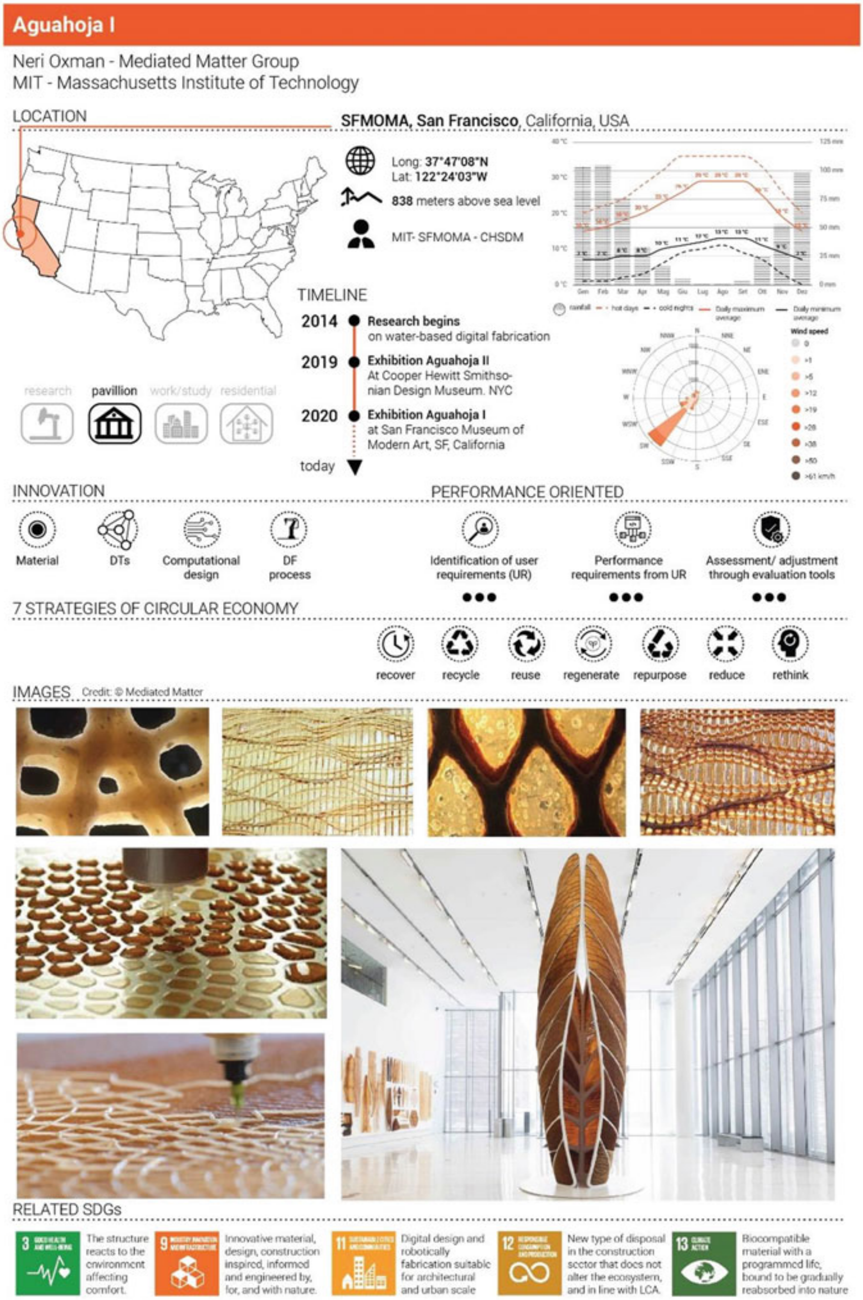

Fig. 2 Aguahoja I case study resume form

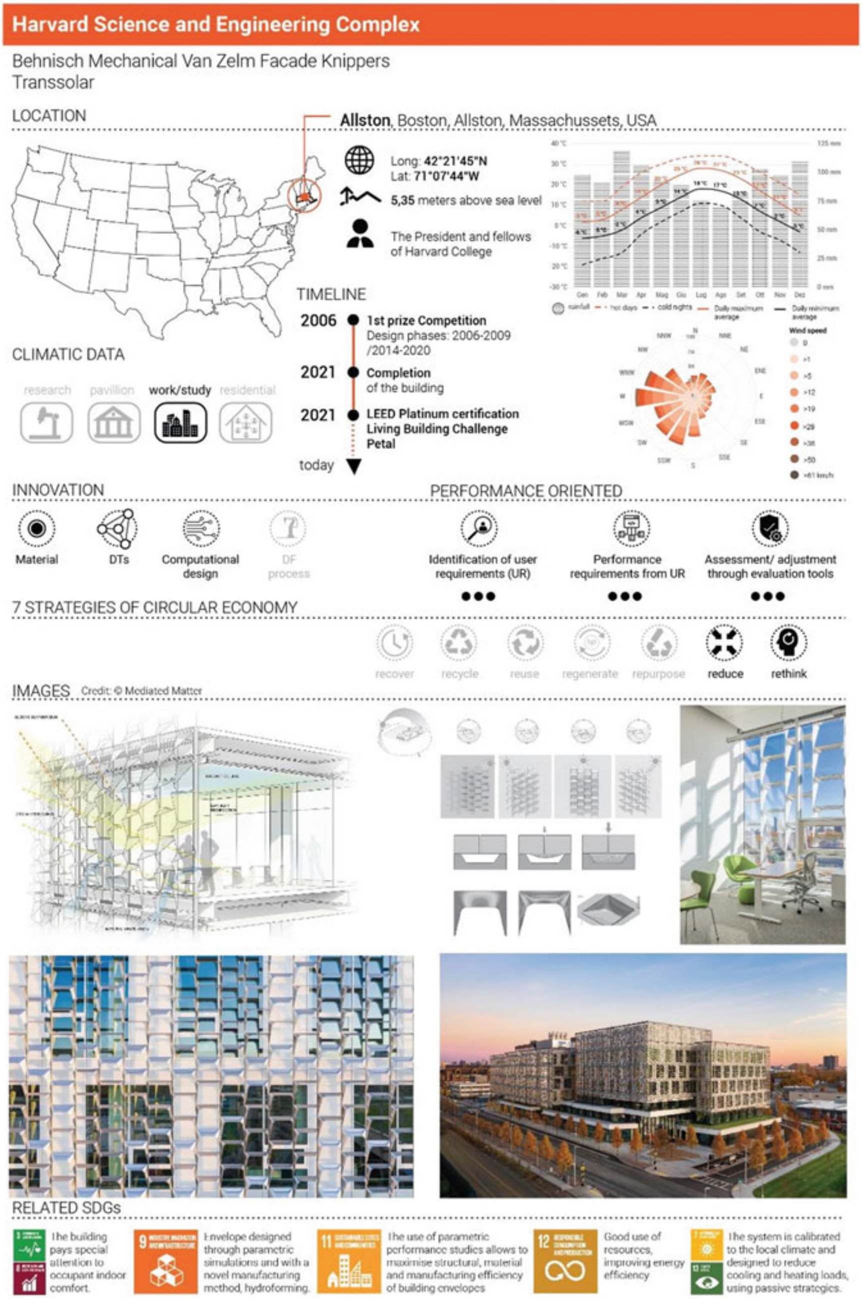

Fig. 3 Harvard science and engineering complex case study resume form

Technology ecosystems. This project proves how a coherent and appropriate combination of environment, technology and architecture can achieve excellent aesthetic quality, a high-performance building envelope and energy efficiency.

4.4 J-Office

The project (Fig. 4) consists in the conversion of a dilapidated building from a warehouse into an architectural design studio located in an old industrial park in Shanghai, China [13].

The concept of the Silk Wall, the external wall that surrounds the warehouse, was developed starting from the manipulation of simple materials using up to date DF processes. In particular the wall consists of cement blocks, angled to create an interesting texture that varies the amounts of light into the building. These cinder blocks are used throughout China since they are so inexpensive, but they are extremely rigid in form and dimension. Thus, the exploration of the material limits led to the use of the blocks with a different bricklaying method by creating stacking algorithms.

IIoT stack. Parametric processes have been used to superimpose the patterns, the contours and definition of silk forms while allowing the wind to enter. To develop the design concept, an algorithm was designed to force a rotation of each cement block.

Agile approach. After an issue appeared during the construction phase, thanks to the advantages of parametric design, a series of alternative results were soon produced by adjusting the parameters, and, after a short calculation, a range of options was identified. This project shows the advantages of parametric design not only in the initial design phase but especially in the construction and management phase: by simply adjusting some parameters, a short calculation is able to offer a range of options and display a series of alternative results.

Technology ecosystems. Computational optimization in the design phase helps to adjust fabrication layouts according to known computer numerically controlled (CNC) technologies [14].

4.5 Living Places

The project (Fig. 5) suggests a new way of thinking focused on building a better living environment that benefits both people and the planet.

Technology ecosystems. Assuming that all phases of the project development must be taken into consideration, the project is meant as an open-source development model that takes into account its entire lifecycle, enabling a new holistic approach to sustainable construction. In fact, by using low impact materials and by considering all stages of the building's life cycle and understanding the implication of each design choice, it is possible to reduce emissions by up to 75% while meeting the demand for

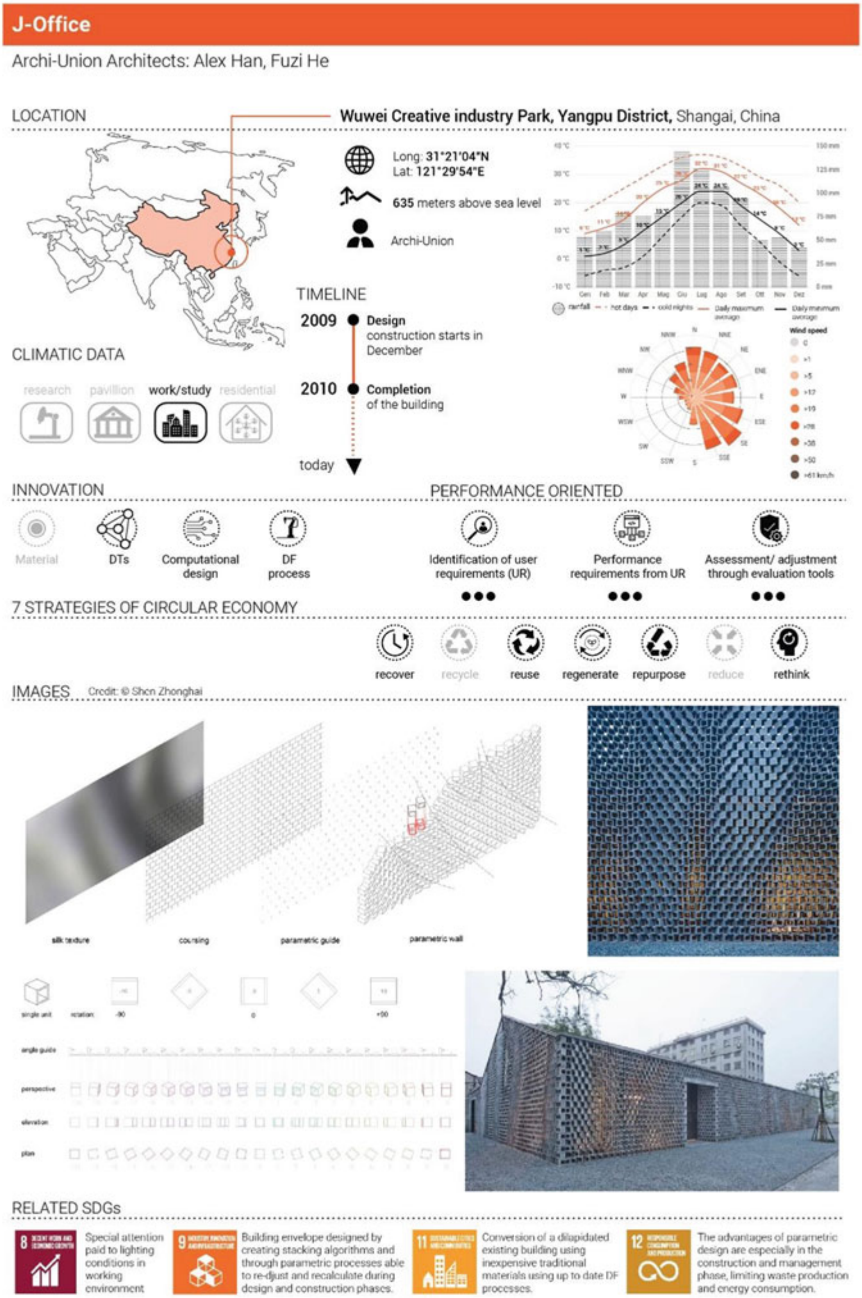

Fig. 4 J-office case study resume form

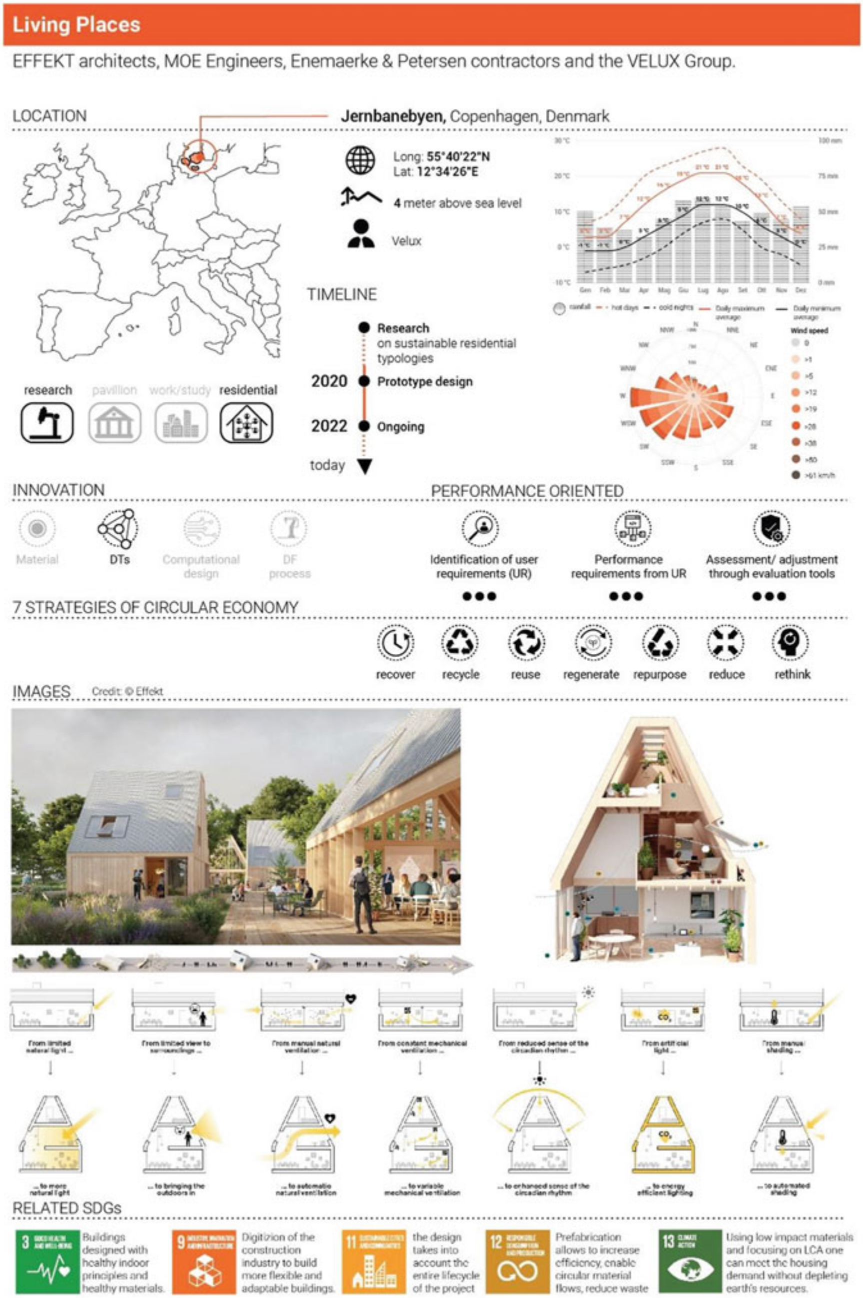

Fig. 5 Living places residences case study resume form

increased housing without depleting the earth's resources. By separating technical systems and building systems the prototype uses circular economy as a means to extend the building's lifetime and reduce cost, labor and waste [15]. The Build for Life approach comprises seven strategic drivers (flexibility, quality, environment, health, community, local, affordability) making up the Compass Model, which is meant to guide the design and building process, providing stakeholders with a framework for reaching an outcome that is sustainable on multiple levels [16]. This solution offers a simple modular building system that requires little to no maintenance and can easily be disassembled and thus repaired or retrofitted during its lifespan.

Agile approach. Moreover, Living places is conceived as a toolbox of different housing typologies that are context-responsive and designed to constantly adapt as occupants' needs change over the day, the year, and the lifetime. The project stands out for its people oriented approach in the definition of the demand-performance framework aimed at acquiring an holistic and integrated understanding of the occupants' needs. In fact, special emphasis is paid to daylight, thermal comfort, air quality, acoustics and outdoor connection [17].

IIoT stack. Overall, digitizing the construction industry and through prefabrication one can increase efficiency and enable more sustainable development, reducing waste, and enable circular material flows.

5 Conclusions

These projects all reveal the strong need—within the construction practice—for innovative processes and technologies that recognize the importance of sustainable design and overcome the inefficiency and lack of interoperability present in the sector [18]. The role of technological culture, together with a performance-driven approach, interdisciplinary dialogue and the creation of a growing information content are essential to manage innovation in the context of digital eras [19]. At the same time, DTs, such as the Internet of Things (IoT), big data, and data analytics, are considered essential enablers of the circular economy (CE) [20]. In fact, the combined methods of computational design and robotic fabrication have demonstrated potential to expand architectural design. Above all, factors such as material use, energy demands, durability, GHG emissions and waste production must be recognized as the priorities over the entire life of any architectural project [18]. To this end, the potential of DTs, DF, and performance oriented design is remarkable for achieving sustainability according to the well-known broad definition (Brundtland Report 1987) of SD as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' [21].

References

1. Geissdoerfer, M., Savaget, P., Bocken, N.M., Hultink, E.J.: The circular economy–a new sustainability paradigm? J. Clean. Prod. **143**, 757–768 (2017)
2. Ghisellini, P., Cialani, C., Ulgiati, S.: A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. **114**, 11–32 (2016)
3. Poljanšek, M.: Building information modelling (BIM) standardization. European Commission (2017)
4. Bocken, N.M., Short, S.W., Rana, P., Evans, S.: A literature and practice review to develop sustainable business model archetypes. J. Clean. Prod. **65**, 42–56 (2014)
5. Adam, R.J., Smart, P., Huff, A.S.: Shades of grey: guidelines for working with the grey literature in systematic reviews for management and organizational studies. Int. J. Manage. Rev. **19**(4), 432–454 (2017)
6. Yin, R.K.: Case study research: Design and methods, 3rd edn, Vol. 5. Sage, Thousand Oaks, CA (2009)
7. Pérez, M.G., Früh, N., La Magna, R., Knippers, J.: Integrative structural design of a timber-fibre hybrid building system fabricated through coreless filament winding: maison Fibre. J. Build. Eng. 104114
8. University of Stuttgart Maison Fibre—Towards a New Material Culture. https://www.itke.uni-stuttgart.de/research/built-projects/maison-fibre-2021/. Accessed 02 May 2022
9. Mogas-Soldevila, L., Duro-Royo, J., Oxman, N.: Water-based robotic fabrication: large-scale additive manufacturing of functionally graded hydrogel composites via multichamber extrusion. 3D Print. Addit. Manuf. **1**(3), 141–151 (2014)
10. Milasi, M.: Aguahoja: il composto organico che ci salverà dalla plastic. https://www.domusweb.it/it/design/2019/03/25/aguahoja-il-composto-organico-che-ci-salver-dalla-plastica.html. Accessed 05 May 2022
11. Behnisch, S.: Architecture for research: humane and sensible building design should address scientists' needs and wishes. EMBO Rep. **23**(3), e54693 (2022)
12. Siu-Ching, M., Matthew R., Schieber, R.: Hydroformed Shading: A Calibrated Approach to Solar Control (2020)
13. Divisare Archi-Union Architects J-Office. https://divisare.com/projects/371379-archi-union-architects-zhonghai-shen-j-office. Accessed 17 May 2022
14. Wang, S., Crolla, K.: Disciplinary isolation-opportunities for collaboration between digital practices and manufacture in china's PRD
15. Effekt-Living Places. https://www.effekt.dk/buildforlife. Accessed 20 May 2022
16. Cutieru, A.: VELUX and EFFEKT Develop Strategic Framework for Designing Healthier and More Sustainable Build Environment. https://www.archdaily.com/971907/velux-and-effekt-develop-strategic-framework-for-designing-healthier-and-more-sustainable-build-environment. Accessed 20 May 2022
17. Build for Life, Velux. What if our buildings could be healthy for both people and planet? https://buildforlife.velux.com/livingplaces/. Accessed 20 May 2022
18. Agustí-Juan, I., Habert, G.: An environmental perspective on digital fabrication in architecture and construction. In: Proceedings of the 21st International Conference on Computer-aided Architectural Design Research in Asia (Caadria 2016) Caadria (2016)
19. Chiesa, G.: La prassi progettuale esplicito-digitale e l'approccio prestazionale. Techne **13**, 236 (2017)
20. Kristoffersen, E., et al.: The smart circular economy: a digital-enabled circular strategies framework for manufacturing companies. J. Bus. Res. **120**, 241–261 (2020)
21. Diesendorf, M.: Sustainability and sustainable development. Sustain. Corp. Challenge 21st Cent. **2**, 19–37 (2000)