Additive Manufacturing for the Circular Built Environment: Towards Circular Construction with Earth-Based Materials

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Author(s):
Chadha, Kunaljit; Dubor, Alexandre; Cabay, Edouard; Tayoun, Yara; Naldoni, Lapo; Moretti, Massimo

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Chapter 7
Additive Manufacturing for the Circular Built Environment: Towards Circular Construction with Earth-Based Materials

Kunaljit Chadha, Alexandre Dubor, Edouard Cabay, Yara Tayoun, Lapo Naldoni, and Massimo Moretti

Abstract By making rapid prototyping accessible and inexpensive, additive manufacturing (AM) has transformed the fabrication industry. The adaptability of the process to various materials makes it applicable to multiple fields ranging from complex nanoscale production in the medical field to the manufacturing of large-scale structures in the construction industry. AM methods are constantly evolving, enabling the production of complex products with minimal initial investment. AM processes generate little waste and require no formwork, making them relevant to the construction industry, which conventionally produces significant amounts of waste.

This chapter provides a high-level overview of AM as an innovative technique and key developments towards its use for a circular built environment. It further delineates the viability of AM techniques using earth-based materials for implementing a circular economy in the construction sector through a series of case studies developed gradually from the scale of architectural prototypes to realised buildings. These examples address factors such as fabrication processes, techniques, and materials used and their influence on circularity through the production cycle of construction achieved using AM. Through the case studies, the chapter promotes 'closing the loop' on resources by reusing and recycling excavated construction materials. The chapter concludes with projections for AM practices and potential commercial applications of the technology. Overall, the chapter is useful for anybody interested in the built environment looking at alternative and sustainable building methods, including users, researchers, and professionals.

Keywords Excavated materials · Circular earthen construction · Additive manufacturing · On-site automation · Sustainable architecture

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K. Chadha (✉)
ETH Zurich, Zurich, Switzerland
e-mail: chadha@arch.ethz.ch

A. Dubor · E. Cabay · Y. Tayoun
Institute for Advanced Architecture of Catalonia (IAAC), Barcelona, Spain

L. Naldoni · M. Moretti
WASP S.R.L, Massa Lombarda, RA, Italy

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7.1 Introduction to Additive Manufacturing

To understand additive manufacturing (AM), it is imperative to know the context of digital fabrication within which the technology was initially developed. Digital fabrication (dfab) is a manufacturing workflow that employs computer-controlled machinery and tools to materialise objects from digital designs. Dfab is classified within the context of the third industrial revolution. The first revolution focused on mechanising manufacturing processes, while the second aimed at the mass production of parts. The third revolution centred on using digital technology, such as electronics, microprocessors, and the Internet, to change the way of working, communicating, and accessing information. It laid the groundwork for the fourth industrial revolution, which focuses on integrating physical and digital information using robotics, sensors, and artificial intelligence (Groumpos 2021).

Dfab has contributed to transforming the nature of working processes and proposed new solutions. Digital fabrication links digital technologies such as computer-aided design (CAD), computer-numerical-control (CNC) machines, and robotics, which are all part of the broader digital revolution. Dfab mainly covers three fabrication processes:

- Additive manufacturing (AM) is a computer-controlled technology for making components by depositing subsequent layers of material to form a three-dimensional object.
- Subtractive manufacturing (SM) is a process where the material is removed from a solid block or stock of material using various tools such as drills, milling machines, wire cutters, lathes, or routers to create desired shapes.
- Formative manufacturing (FM) is a range of techniques that involve the mechanical deformation, bending, forging, or shaping of a given material, with or without the use of a mould.

Due to the versatility of its fabrication process, cost-effectiveness, and accessibility, AM appears to be the preferred dfab technique for mass customisation. This process has been explored with various materials such as plastics (Wei Keat and Chow 2022), metals (Huang et al. 2023), ceramics (Chen et al. 2018), composites (Korkees et al. 2020), and biomaterials (Malik et al. 2020), to name a few.

Within the wide range of AM processes, seven subprocesses fall under the AM umbrella: binder jetting, directed energy, deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerisation (Slotwinski 2014). Each AM process offers the flexibility to fabricate a wide range of complex shapes and hence was soon adopted by the industry for rapid prototyping depending on the scale and resolution of its application. Even though 3D printing (3DP) and AM are defined as the same fabrication technique (Ngo et al. 2018), a deeper understanding of the process and its parameters indicates that 3DP is a subset technique of AM processes: in contrast to 3DP, which builds three-dimensional objects by adding material in successive layers, AM creates three-dimensional objects by adding material, which may or may not be produced with consecutive layers (McCormack et al. 2020; Ming et al. 2022).

Schematically, AM utilises a computer and 3D printer to produce custom physical objects. CAD software generates 3D digital objects, and computer-aided manufacturing (CAM) or slicer produces slices of a 3D geometry, resulting in a geometric code (G-code). The G-code provides positional data, velocity, and extrusion rate values for the printer nozzle, which is moved by a motor-driven CNC system following instructions. This streamlined software and hardware infrastructure enables quick, low-cost, and highly customisable production of bespoke physical objects using AM. Several sectors, including robotics, medicine, food science, architecture, and others, have extensively used AM (Shahrubudin et al. 2019). AM has significant potential in the fields of surgery, disease modelling, organ printing, veterinary medicine, and tissue engineering (Bozkurt and Karayel 2021).

AM processes are not restricted to a particular machine configuration and can be customised to suit generic tools such as industrial robots (Pham et al. 2016). This offers advantages in terms of application scalability, operational efficiency and accuracy, versatility in executing diverse functions, and agility for multitasking. The adoption of AM process methodologies across various machine configurations has facilitated the expansion of the technology and its implementation within the built environment.

7.2 Additive Manufacturing in the Built Environment

AM processes have found their way into construction, automating dull, dirty, and dangerous site operations (Jud et al. 2021). AM methods have formed a mass-customisable production system, with 3DP as the preferred option due to its waste-free and formwork-free nature. Within the wide range of AM processes, two specific processes have been explored at the architectural building scale:

- *Material extrusion* is a fast AM method in which continuous layers of materials are deposited one on top of the other while the material is in a plastic state. The adhesive characteristics of the material and gravity determine the interlayer bonding between the layers to form a monolithic structure. The Contour Crafting technique (Khoshnevis et al. 2006) pioneered technologies to introduce material extrusion to the building industry. By linking trowelling and extrusion processes, Contour Crafting improved the surface quality faster in the built volume.
- *Binder jetting* is a high-resolution AM method in which a printer selectively deposits a liquid binder onto a bed of powder particles to build fine-resolution objects. In 2006, D-Shape (Gardiner and Burry 2010) technology presented the first demonstration of their machine to create high-resolution architectural scale structures. D-Shape introduced a new manufacturing stream of material-efficient, gravity-independent, high-resolution objects that could apply to the built environment.

While both processes have allowed for the use of a wide range of possibilities in terms of print resolution and material usage, the construction sector considers material extrusion a feasible alternative owing to the reduced number of peripherals needed for equipment installation, the faster building rate, and the scalability of the process (Puzatova et al. 2022). Another aspect influencing their choice is the ability to print directly on the construction site. In this context, there are three important criteria for adopting AM in the building industry: (a) building material, (b) machine configuration, and (c) computational design methods. The validation of these factors is made possible by the expertise of professionals and experts in the field, allowing for the effective deployment of different large-scale AM applications.

7.2.1 Materials

With the surge in the availability of large-scale construction format AM machines such as BOD II (COBOD International A/S 2017) and Crane WASP (WASP Srl 2018), the building sector was able to investigate various materials on a construction scale, including plastics, metals, and plaster. Nevertheless, material durability, size restrictions, and a slow production rate have limited these material systems to smaller building components, which has led to cementitious materials being the material of choice for structural building elements. After all, concrete is one of the most widely used building materials with superior structural properties, availability, and affordability (Crow 2008). Even though concrete processing is being improved and more automated, conventional construction activities that use concrete still generate a lot of waste and have high energy consumption.

In this context, 3D concrete printing (3DCP) has been the first AM technology to enter the construction industry, with the promise of an effective, customisable, and waste-free form of construction. Rapid growth in using 3D printers for building has highlighted the need to develop new material control systems, especially those that allow precise control over the material's hydration, rheology, and curation rate, which is critical for achieving volumetric buildup (Jones et al. 2018).

However, the consumption volume of concrete and the chemicals added to accelerate the mix to facilitate 3DP make the process less structurally capable while possibly being even more harmful to the environment per volume (Flatt and Wangler 2022), exposing the need for alternative sustainable materials for 3DP such as excavated earth and geopolymers. In particular, earth-based material offers a significant advantage in terms of transportation and sustainability, as it can be extracted and processed directly on site. It is known for allowing the construction of sustainable, healthy, and thermally efficient buildings (Minke 2013). It is also a material linked to old construction techniques requiring extensive skills and manual labour, issues that could be solved with 3D printing machines.

7.2.2 Machine Configurations for Additive Manufacturing

In addition to material control, the successful implementation of additive manufacturing (AM) operations at the building scale relies on the effective integration and accessibility of material processing machines and fabrication machine configurations. The choice of machine setups for AM in construction is contingent upon factors such as size formats and mobility. Consequently, various machine and robotic configurations have been employed in this context. Broadly, these configurations can be classified into two groups: off-site and on-site manufacturing setups.

Off-site manufacturing setups entail the construction of components within a controlled factory environment, followed by transporting prefabricated customised parts to the construction site for assembly, ultimately forming a complete building structure. Using off-site manufacturing facilities ensures regulated conditions that shield production machinery from ambient fluctuations such as temperature and humidity, thereby enabling the mass production of high-quality products. To achieve this, rigid frame Cartesian-type machines (Khoshnevis et al. 2006) are commonly employed, offering three or five degrees of freedom depending on the specific application requirements. When more intricate fabrication operations are necessary, setups incorporating a robotic arm mounted on a Cartesian gantry (Anton et al. 2020) are being implemented. This configuration allows for the gantry's robust manipulation capabilities and the robotic arm's dexterity and precision, thus accommodating large-scale construction while maintaining high-resolution detailing.

On-site manufacturing setups vary in configurations, ranging from fixed machines with predetermined footprints to autonomous setups capable of movement and localisation within the construction site. Agility and precision are crucial for these setups to respond and adapt to the dynamic site conditions. Besides large-scale Cartesian 3-axis machines, researchers are exploring using robots on mobile platforms like the In Situ Fabricator (Giftthaler et al. 2017) and digitally controlled construction machinery (Jud et al. 2021) for construction operations.

Such machines have demonstrated applicability ranging from component-based architectural structures to full-scale in situ structures. While off-site manufacturing setups require additional peripherals, it allows for the fabrication of building components in a controlled environment (Gomaa et al. 2023). Thus, it avoids delays due to dynamic site conditions and widens the potential of testing the application of novel construction materials. On the other hand, on-site machinery reduces transportation overheads and produces larger objects, often directly in situ (Dubor et al. 2018). The role of this on-site machinery includes material sourcing, material processing, and building procedures. Additional machines might be required to process materials sourced from the site and surface finishing operations.

7.2.3 Computational Methods

The paradigm shifts in architectural design, in which architects use more digital tools, parametric modelling, scripting, etc., to produce geometries providing an approach in which design-generating parameters may be changed on the go using intelligent systems such as machine learning (Guo Liang and Yeong 2022). In AM processes, such a parametric computational design approach acts as a 'middleware' in the workflow between generated digital designs and the already manufactured sequence. This allows a control to adjust relevant process parameters. The role of computational design tools is critical since most AM processes are time sensitive and need application-specific information exchange between the parameters.

Like the approach of dfab, AM processes involve integrating design and manufacturing processes within a single digital environment to reduce the gap between design and fabrication. Such control over the process in AM on a building scale is beneficial when site conditions and material qualities vary. Because of the parametric control workflow, it is now possible to model and record previously unanticipated material and site conditions change to effectively adapt to construction errors. This allows for the emergence of novel, cost-effective, and fabrication-aware individualised design solutions.

7.2.4 Summary

AM has established a new construction domain that can be generated digitally and has also addressed the construction sector's problems of low productivity and waste generation. Yet the materials presently used for AM have severe environmental impacts owing to the material's high embodied carbon and one-time use (Faludi et al. 2015). The following section will address the inclusion of AM processes within a circular economy framework, highlighting the essential characteristics that render AM a feasible option for transitioning towards a circular built environment.

7.3 Additive Manufacturing for a Circular Economy

7.3.1 Advantages

AM enables product innovation through design freedom of mass customised and cost-effective components. It further presents unique features to support circular economy initiatives, such as waste-free production and the opportunity to test novel sustainable material systems promoting product durability and reuse. Consequently, AM has been adopted by various sectors to reduce environmental impacts. The overview from the preceding section about the diverse application of AM highlights its status as a technology driving the transition to a circular production system, which results in the reconfiguration of the supply chain, laying the groundwork for attaining a circular economy. The advantages of employing AM within a circular economy include the following (Hettiarachchi et al. 2022):

- Resource efficiency and minimal waste generation due to the selective deposition of the AM processes.
- Reduction of transportation-related environmental and economic impacts through the on-demand production of customised, locally produced products.

- Diverse material applications adopting the strategy of design for disassembly with prefab components help in easy and clean disassembly for reuse and local repair.
- Flexibility to use excavated and recycled materials, which reduces the environmental impact caused due to the embodied carbon of the materials.
- Individualised production to help in the renovation and restoration of buildings.
- Flexibility to adjust and optimise each component to its individual needs and situation.
- The use of novel standard and non-standard material in the AM process.
- Adaptability for making connections that adapt to the uniqueness of various material systems.

7.3.2 Additive Manufacturing in a Circular Built Environment

Resource efficiency is a key factor in AM stepping up to a building scale in the built environment context. The article presented 'An Emerging Framework for the Circular Digital Built Environment' (Çetin et al. 2021) identifies four distinct resource strategies to achieve the CE concept in the built environment: narrowing the loop, slowing the loop, closing the loop, and regenerating the loop. Building on this framework in the context of a circular built environment, AM showcases an impactful building solution: AM process allows for optimised material use for manufacturing, thereby 'narrowing the loop' by using less material to construct and generate minimal waste. The durability of the products achieved by the computational design workflow using CAD software helps 'slow the loop' by efficiently using material through geometric optimisation and targeted component repair, instigating a longer life cycle. Additionally, the materials used contribute significantly to the efficiency of the circularity process by 'closing the loop' by allowing the use of reclaimed and recycled materials. The freedom of using naturally sourced, nonconventional materials helps in the 'regenerating loop' of the product cycle by facilitating the disposal of materials upon the completion of the cycle.

The circularity of a building in AM processes is considerably affected by activities related to both the machine configuration and the materials employed, as they are closely dependent on the environmental and economic impact linked to their sourcing, manufacturing, and transportation. These operations include transporting resources for off-site manufacturing of stock materials or equipment transportation for on-site manufacturing setup. While prefabricated parts are often preferred in the construction industry due to quicker construction times, enhanced quality control, product durability, increased safety, and decreased waste, on-site manufacturing offers several advantages, including low environmental impact and high levels of customisation in construction.

7.3.3 Summary

Consolidating science-based information on building components' greenhouse gas emissions (GHG) and related activities across their full life cycle is an important feature of implementing climate mitigation methods. In the context of the built environment, it is particularly informative to look at the emissions resulting from processes preceding the occupancy of a building early into the sourcing of construction materials: 'Quantitatively, the phases of material manufacturing, transportation, and on-site construction were responsible for 94.89%, 1.08%, and 4.03% of energy consumption, respectively, and 95.16%, 1.76%, and 3.08% of global warming potential' (Hong et al. 2014). While both off-site and on-site systems rely on transporting material or equipment from another location, the use of a kilometre-zero (km-0) approach in construction would prove to be an effective instance of AM in a circular built environment, promoting social, environmental, and economic sustainability (Farias et al. 2017). The km-0 strategy first appeared in the slow food movement to promote the consumption of local ingredients, reducing the distance between producers and consumers (Souza Eduardo 2021). In the framework of a circular built environment, this would include construction using only locally available building resources and materials benefiting from natural and low-impact processing. The following section will focus on 3D printing with earth (3DPE) as an effective solution for AM in a circular built environment using excavated sustainable and recyclable material primarily consisting of raw earth.

7.4 Case Studies

Because materials used in AM (such as cement mortars, plastics, and metals) are environmentally damaging due to their embodied carbon content and supply chain, exploring alternative materials of a more circular nature is crucial. Raw earth is a readily available material and presents a traditional precedent use in the field of construction. Traditional building techniques using unprocessed earth have evolved through centuries of local knowledge. They need minimal energy for construction, but these solutions are not competitive due to their labour-intensive nature and slow building pace (Minke 2013). Alternatively, 3DPE has upgraded the conventional earth building methods of direct shaping and extruded earth by combining them with computer-controlled machines and improved safety and control over the construction process while keeping the environment and performance benefits of traditional earth construction. The process of 3DPE demonstrates a construction system capable of minimising greenhouse gas emissions (GHG) from construction components, achieved through the use of km-0 robotic AM.

7.4.1 Introduction to 3D Printing with Earth

3DPE methods use the layer-based AM approach, comparable to the Contour Crafting method using earth-based materials. In contrast to other additive manufacturing (AM) processes used in the construction industry, such as 3DCP, 3DPE stands out for its ability to avoid the use of environmentally harmful chemicals to speed up the material curing process. Instead, it combines water and aggregates to achieve the necessary level of malleability for 3D printing. In 3DPE, the walls of the construction components are connected using infill. This helps create a load-bearing volume with enough structural depth. These infills provide more practical structural features, such as incorporating electrical and plumbing services, a network of air cavities for natural ventilation, adding a filler material to augment heat lag, etc. (IAAC 2022). By adopting 3DPE, there is a significant reduction in operating energy and a more efficient resource consumption loop. This is achieved by closing the cycle, which minimises the energy consumption required to operate the building. As depicted in Fig. 7.1, a crucial feature of 3DPE is the seamless integration of on-site processes, starting from excavation to the final detailed finishes in the constructed building, utilising locally sourced materials.

3DPE presents an alternative building method with a circular design-to-construction life cycle consideration of the built environment, which counteracts the tendency of excessive energy consumption in building operations. Additionally, the

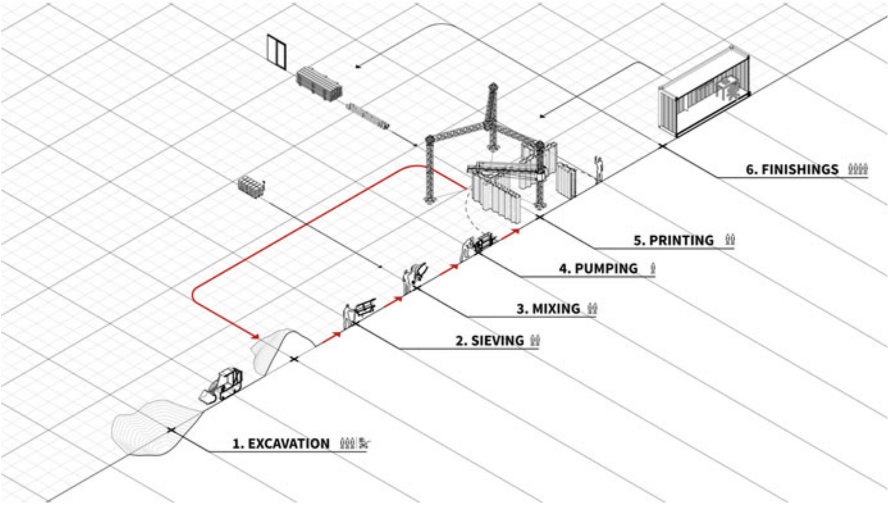

Fig. 7.1 Suggested construction scenario for on-site 3DPE excavating the material using Crane WASP. The illustration portrays the distinct phases of the supply chain, starting with material acquisition and processing, followed by the construction process, resulting in the final product of a constructed building. Highlighted in red indicates the stage at which the material can be recycled and reintroduced into production, forming a circular use of the excavated material

different aspects of a 3DPE construction process, plus the use of local labour and participation in local economies across its value chain and its accommodation of complex and innovative building models, showcase the circularity of 3DPE as a construction system that closes the loop of circularity in a building process. The following subsections present three case studies demonstrating large-scale implementation of 3DPE that indicate how the transition from an off-site to an on-site mode of a 3DPE building significantly affects the circularity of the building. In addition, the case studies also display the integration of wooden components with 3DPE in ways that add architectural functionality to the built structure.

7.4.2 Digital Adobe: Prefabricated Components Manufactured Off-Site Using Recyclable Materials

The first case study presents *Digital Adobe*, developed during the OTF 2017–2018 course at IAAC and built in the Valldaura Campus of IAAC (IAAC 2018). It is a 2-metre-wide and 5-metre-high printed clay wall with a varying thickness (0.7 m at its bottom and 0.2 m at its top) with a wooden slab resting on the wall at 2.6 m to simulate a clay/wood building unit, where the connections between two materials and the vertical load from a horizontal slab can be tested. Digital Adobe serves as the first large-scale exploration of combining 3DPE and wood elements where the 3D printed earthen component takes the compression load of the structure, and the wooden spanning element works in tension (Fig. 7.2).

The primary focus of the case study was to explore the climatic and structural performances of 3DPE. With the long-established understanding of clay's thermal properties to moderate heat transmission, the team has sought a design to enhance such properties. To limit temperature transfer from one side of the wall to the other and to improve the compressive strength of the wall, the infills were filled with unprocessed soil. A ventilated wall design reduced summer heat gain through convection between the openable top and bottom openings. It retained heat in the winter when both openings were closed.

The material mix consisted of conventional adobe mix, including clay, sand, silt, and aggregates. Vegetable enzymes are used to reach the grade of the fluidity of the material mixture needed to achieve the flow rate required to extrude the material for 3D printing. The prototype was partially built with recycled material from the preceding research of On-Site Robotics at IAAC in 2017. Around two tonnes of material from On-Site Robotics (Dubor et al. 2018) was recycled, making up almost half of the prototype's total material source. To make the recycled material usable for 3DPE again, it was crushed and rehydrated using a much-reduced number of enzymes. Finally, 'closing the loop' in resource management was proven by the recycling and reusing process.

Fig. 7.2 Digital Adobe (2018) is the outcome of research on 3DPE for a performative habitat. Design parameters in robotic construction enhance climatic and structural properties innate to the material. Thermal properties such as transmittance are regulated by robot precision through the geometry design of the global shape, surface texture, and ventilating cavities. (© Dongliang Ye)

7.4.3 *TECLA: On-Site Construction Using Excavated Materials*

TECLA (WASP 2022) is an innovative circular house unit built in Massa Lombarda by WASP and Mario Cucinella Architects (MCA), integrating research on vernacular building techniques with natural and regional materials. TECLA was constructed using two synchronised printer arms concurrently, utilising industrial automation protocols to optimise mobility, avoid collisions, and ensure efficient operation. Each printer unit has a printing surface of 50 square metres, allowing for the rapid construction of house modules. TECLA has a floor size of 60 square metres; it comprises a living zone with a kitchen and a night zone with services. The structure is a composition of two continuous elements that, through a sinuous and uninterrupted sine curve, culminate in two circular skylights that produce zenithal lighting (Fig. 7.3).

In addition, the composition of the earth mixture responds to local climatic conditions, and the filling of the envelope is parametrically optimised to balance thermal mass, insulation, and ventilation according to the climate needs. The materials used were local soil of 6 mm maximum aggregate size, sand, rice husk, and Mapesoil, a lime-based binder added at 5% by weight of the batch.

The proposal was centred on environmental variables, particularly solar analysis, which was the design driver behind the undulated surface and increased the total surface area of the outer facade. Using computational tools to create climate-responsive shapes to improve raw earth's physical qualities ensures increased passive energy performance of built structures.

Fig. 7.3 The sustainable, innovative TECLA model (2021) of on-site housing construction uses materials sourced from the construction site and constructed using the modular Crane WASP machine. (© WASP)

7.4.4 TOVA: On-Site Construction with Excavated and Recyclable Materials

TOVA is a building prototype (IAAC 2022) demonstrating the potential of 3DP with sustainable materials in response to increasing climate challenges and related housing emergencies. It was built in the Valldaura Labs facility in Collserola Park, on the outskirts of Barcelona. The construction spans 7 weeks and uses a Crane WASP modular printer and km-0 materials. Using local materials sourced within a 50-metre radius reduces the environmental impact of transportation and waste generation during construction. TOVA can be studied as a near-zero emissions project: the design is tested via digital and physical simulations to reduce carbon footprint, considering the life cycle assessment of the building components. The circular design approach is aimed at designing an environmentally responsive building constructed from reusable biomaterials across the construction phases as follows: a geopolymer foundation, a framework made of local earth, mixed with additives and enzymes to ensure the structural integrity and material elasticity necessary for the optimised 3DP of the house, a locally sourced timber roof structure, and wooden carpentry. To improve the material's longevity and weather resistance, a waterproof coating is added using raw extracted materials such as egg whites.

The building design of TOVA is based on a precise site condition of the Mediterranean: the volume is compact to protect from the cold in winter, yet expandable for the other three seasons. For this purpose, the wall section, composed of six earth surfaces and a network of cavities containing air or insulation, was calculated to prevent winter heat loss while protecting from summer solar radiation. The result is a climate-responsive building: the design considers digital and physical simulations to reduce construction footprints, monitor the reduction of greenhouse

Fig. 7.4 TOVA (2022) is a completed circular building prototype using locally sourced materials constructed with 3DP processes achieved by a layer-based deposition of earth material mixture and a timber wood structure and a network of cavities in the wall that participates in the climate-responsiveness of the building. (Photographs by Gregori Civera)

gas emissions, and consider the life cycle assessment of the building components. It also demonstrates the valuable knowledge of traditional material craftsmanship in informing a technology-driven association for establishing circular constructions in the built environment (Fig. 7.4).

The implementation of on-site printing techniques and the use of natural materials in 3DPE guarantee the circularity of the construction process. As no chemical modification is needed to recycle the structure at the end of its life, it effectively prevents residual waste and pollution. The printed earth layers are returned to the source of the material, completing a full loop of circularity in the construction cycle.

7.5 Discussion

Three critical developments have allowed for the widespread use of AM in the construction sector:

- *Accessibility to machines*: The advancement of lightweight and modular construction machinery, such as the Crane WASP, has led to the widespread adoption of on-site construction services utilising materials from companies like Icon3D (USA), Cobod (Denmark), Tvasta (India), and WASP (Italy). These innovations have significantly expanded their presence and usage on a global scale.
- *Material processing techniques*: In the specific case of 3DCP, rheological control of material processing machines was a key breakthrough for ensuring the ‘set on demand’ behaviour of the material to enable structural buildup during printing. In upcoming years, these concepts could be extended to more sustainable processes

such as 3DPE to increase build rate and construction efficiency to make the earth construction market competitive.
- *Training design professionals*: The emergence and constant evolution of new AM processes for construction require special skill sets for operators to use such technologies efficiently. From an academic standpoint, teaching and preparing the next generation of professionals is crucial for effectively managing these complex technological environments. It is crucial that the designs coming out of such a process are optimal for the technology in terms of material and structural efficiency.

The broad implementation of AM globally will be aided by the availability and accessibility of digitally controlled machines for processing material and fabricating. With the rising concerns over the sustainability of the construction industry, the focus will be on AM technologies that use sustainable materials. With a surge of technologies such as 3DPE, the applications might expand in extreme scenarios to form a sustainable, on-site, waste-free construction process. 3DPE has the potential for various uses, from emergency shelters in rural settings with plentiful local resources but limited masonry skills to commercial residences with climate-responsive designs that solve severe climatic challenges.

The complexity of AM processes stems from the interdependency of machine, material, and design characteristics. The presented projects pose limitations regarding durability and efficiency, which imply two future developments needed for research: (1) on a construction site where materials are susceptible to changes in ambient temperature, machine downtime is a significant problem that prevents the technology from being used to its total capacity and thus makes it unaffordable, and (2) in addition to dynamic building site circumstances, material variations throughout construction make it challenging to forecast the precision and effectiveness of the technology. Multi-staged diagnostics, including feedback on the integrity of the material, deformation of the structure, and maintenance areas, will help improve construction quality.

7.6 Key Takeaways

- The introduction of additive manufacturing (AM) as a unique construction method has redefined efficient processes and, when used with sustainable materials, has the potential to reduce the building sector's environmental impact.
- Machine availability and AM professional training are necessary for enabling sustainable on-site construction using sustainable AM materials.
- Using AM and integrating other building components can greatly enhance the design potential for climate-responsive building construction.
- Promoting socially and environmentally sustainable AM processes could lead to a new building system that involves closing the circularity loop via utilising local resources for construction that can be recycled and reused.

- Using local materials and resources allows for a fully inclusive construction process, supporting and boosting local economies by involving various local stakeholders in the value chain. This could lead to the rapid adoption of the AM construction system in countries most affected by climate-related housing emergencies.

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Kunaljit Chadha is a doctoral candidate at Gramazio Kohler Research at ETH Zurich, working on ‘Impact Printed Structures: Adaptive strategies for full scale on-site robotic earth construction’. His doctoral research focuses on developing computational design systems and construction strategies for upscaling the ‘Impact Printing’ process to form an efficient on-site, waste-free building method for earth-based materials incorporating high design and production control levels. Prior to his doctoral research Kunal worked as a lecturer and robotic fabrication expert at the Institute for Advanced Architecture of Catalonia from 2016 to 2021.

Alexandre Dubor is an architect researcher presently leading the AAG fabrication team at IAAC. Together they explore the potential of new technology, materials, and designs for a better construction industry, focusing on 3D printing and robotics for sustainable architecture.

Edouard Cabay is a program head at IAAC, where he directs the 3dPA Master’s Program and the Self-Sufficient Building Research Line. He has been a senior faculty at IAAC since 2011. He has also been the director of the AA Visiting School Barcelona since 2014 and is presently an invited professor at CEDIM in Mexico. Edouard Cabay taught at the Architectural Association as a diploma unit master from 2010 to 2013, at the École Spéciale d’Architecture in Paris as an associate professor from 2012 to 2015, and at the École Polytechnique Fédérale de Lausanne as a first year studio director from 2013 to 2016.

Yara Tayoun is an architect and researcher specialising in the digital and technology-driven transition of circular processes in architecture and design and has worked on cocreating circular resource flows in cities with a focus on wood construction. She is presently the coordinator of the applied research postgraduate programme in 3D Printing Architecture at IAAC.

Lapo Naldoni (WASP) has a building engineering and architecture degree from the University of Bologna, Italy. He developed his thesis on mud constructions and robotic-informed deposition on tensioned fabrics. Presently, he is a member of the Wasp R&D team and works on 3D printing at different scales with polymers and fluid-dense materials. He is a teacher assistant of architecture planning (Prof. Alessio Erioli) at Alma Mater Studiorum, Bologna. He worked as a computational designer at Mario Cucinella Architects (IT).

Massimo Moretti (WASP) graduated in 1974 as an electronic technician, and he started developing products. Massimo Moretti collaborates with research centres, universities, R&D departments, and big national and international companies to create industrial automation projects, 3D modelling, and prototyping in the field of mechanics and interior design, cosmetics, and chemistry. In 2012, together with a group of young designers, he founded WASP (World's Advanced Saving Project), a company that designs, produces, and sells 3D printers made in Italy worldwide. Massimo Moretti, taking inspiration from nature and from the observation of the potter wasp, which builds its own nest with material recovered from the surrounding environment, moves WASP to produce large 3D printers able to build houses with natural materials and available on the territory, at a cost tending to zero.