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Insights into New Trends and Contemporary Challenges in 3D Printing in Architectural Sector

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Abstract. This chapter explores the most recent trends and challenges stemming from the integration of 3D printing within the architectural sector. The rapid evolution of additive manufacturing has brought forth innovative design possibilities, parametric modeling and sustainable material exploration. The discussion provides insights into available 3D printing technologies and methodologies for fabricating architectural products or designs, along with the advantages and challenges that must be addressed to get maximum benefits. To achieve this goal, case studies and current research are examined, with a specific focus on ongoing issues related to housing and environmental needs. Through an analysis of these developments, this contribution highlights the dynamic landscape where technology and architecture intersect, underscoring the necessity of collaborative approaches to fully realize the continuously improving and more sustainable efficiency of 3D printing in shaping the future of the construction field.

Introduction

The origins of 3D printing can be traced back to 1986 when Chuck Hull patented the concept of stereolithography, a process based on photopolymerization that converts liquid materials into solid polymers through curing with a light source [1]. This breakthrough technology paved the way for the improvement of various 3D printing techniques, including Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Powder Bed Fusion (PBF) which are additive manufacturing technologies that have contributed to significant advancements in various industries by providing efficient and cost-effective solutions for rapid prototyping, customization, and small-scale production. The choice of technology always depends on factors such as the required material properties, component complexity and production volume [2].

The additive manufacturing (AM) process concerns adding materials layer by layer until the object is fully constructed, as opposed to subtractive production methods where material is removed to shape the final object [3]. Considered an innovative technology, 3D printing has become an integral part of the fourth industrial revolution, characterized by advancements in digitalization and automation. The Western European market has particularly embraced 3D printing technology, with substantial growth witnessed in recent years. According to International Data Corporation (IDC), a leading provider of market intelligence, the Western Europe market reached $7.2 billion in 2019, growing at a staggering 29.6%, outperforming the global average. According to Global Market Insights, the global 3D printing market is expected to experience significant growth in the next few years. The market size is expected to reach approximately $98.31 billion by 2032, up significantly from $17.38 billion in 2022. This growth trajectory indicates a compound annual growth rate (CAGR) of 18.92% during the forecast period from 2023 to 2032 [4].

In addition, 3D printing significantly impacts research and education by providing researchers, scientists, and students with the ease to prototype experimental models, scientific instruments, and teaching aids. It promotes hands-on learning, stimulates creativity, and opens up new possibilities for interdisciplinary collaboration and exploration. Factors driving the growth of the 3D printing market include advancements in materials and technology, expanding applications in healthcare, automotive, aerospace, consumer goods sectors and the growing focus on product innovation.

This trend is reflecting the increasing adoption of 3D printing across construction industries, even in the architectural and design context, since companies recognize that the rise of 3D printing over traditional production methods can be attributed to several advantages [5]:

Primarily, 3D printing technology facilitates structural innovation by enabling the construction of intricate shapes and structures that were previously unattainable through conventional manufacturing methods. [6]. Secondly, enhanced flexibility emerges in the management of construction sites located in underserved areas or densely populated urban centers. Sustainability is another key aspect of 3D printing technology in architecture and design. By employing 3D printing, the amount of processing waste is significantly reduced, also improving the utilization of local materials according to the circular economy principles. Additionally, this technology facilitates the use of bioplastics and recycled materials, effectively reducing the carbon footprint linked to the building process.

Safety is improved as 3D printing reduces noise, dust and construction site risks through efficient management and minimized overlap [7].

Furthermore, speed allows for rapid prototyping and production of architectural and design products, optimizing material usage and streamlining project timelines [8]

3D printing guarantees a high level of accuracy by directly translating information from the project's 3D model to construction operations. This presents an additional advantage in reducing the likelihood of errors and assuring greater precision in detailing.

Methodology and Structure

This chapter presents a structured analysis that spans three essential sections:

A broad overview on specific literature review with the aim of delivering relevant information about the evolution and applications of 3D printing in the building sector. The section offers an extensive overview of pertinent literature, delving into the evolution of 3D printing within the building sector. Additionally, it examines the diverse range of applications of 3D printing, spanning from rapid prototyping to intricate architectural designs and sustainable construction practices. The intention behind this is to equip readers with a strong foundational understanding of the multifaceted contributions that 3D printing technology makes to sustainable construction practices.

Examining selected best practices in alignment with recent research findings, the analysis concentrates on design methodologies, structural feasibility, and material properties. This is all conducted with the overarching objective of presenting sustainable housing solutions.

A discussion with case studies and an evaluation of practices aimed at understanding to what extent 3D printing can offer a valuable contribution to addressing the increasing housing crisis in critical contexts, while maintaining sustainability principles.

Literature Review

In the early 2010s, researchers primarily focused on developing the fundamental principles of 3D printing for applications in the building sector.

A micro-architecture example. In 2008, D-Shape founder Enrico Dini revolutionized the construction industry by inventing a prototype large-format 3D printer using binder jetting [9].

Specifically, this process mimics the chemical-physical processes involved in the geodynamics of rock formation. The 3D printer works continuously, depositing textured ink onto the sand, forming the object through jets of microdroplets of material, gradually giving it a textured shape, taking approximately 24 hours for the solidification process for each section. The main goal of this innovative technology was to create a trabecular bone structure that could be applied in architectural design and resembled the structural organism of human bone. Collaborating with D-Shape, Andrea Morgante of Shiro Studio designed the Radiolaria Pavilion, a lightweight structure out of magnesium-based materials inspired by the intricate geometries found in the skeletons of microscopic marine organisms with silica shells [10]. Serving as a micro-architecture experiment, the Radiolaria Pavilion, aimed to demonstrate and test the potential of additive manifacturing, employing advanced digital design and fabrication systems (Fig. 1a, 1b). Among the most prominent figures in the field of 3D printing, Behrokh Khoshnevis, an Iranian American engineer and professor, is recognized for his pioneering work on contour crafting, a large-scale 3D printing technique for constructing buildings [11]. This technique is based on computer-controlled robotic systems to extrude layers of concrete and other materials, enabling the rapid construction of entire buildings. The technology aims to streamline the construction process, reduce costs and address housing shortages. Koshnevis has used various prototypes to demonstrate the feasibility of contouring, pushing for the integration of 3D printing into the construction industry.

Saletto et al. (2016) conducted a study focused on the applications of 3D printing for constructing load-bearing concrete walls and building facades in a controlled environment. The aim of their work was to examine various printing techniques, materials and structural designs to assess the mechanical properties and performance of the printed walls, in order to provide valuable insights for creating durable and structurally sound concrete walls [12].

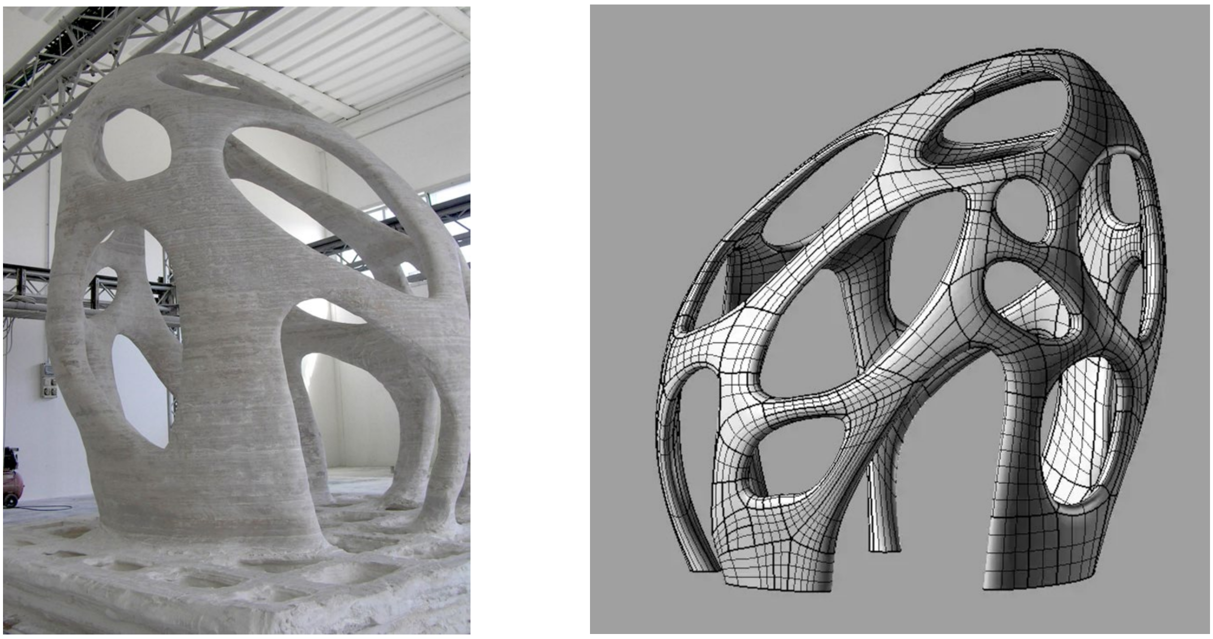

Fig. 1. Radiolaria Pavilion structure and 3D CAD model, saved as an .STL file for the 3D printer.

Speed of Construction and Concrete Printing. Regarding construction speed, back in 2017, Apis Cor and ICON, two American construction technology firms at the forefront of advancing robotics to address the housing crisis, successfully completed the construction of the first single-story residential building using 3D printing, accomplishing the entire project within a 24-hour timeframe. This feat underscored the speed and efficiency that 3D printing can inject into the construction industry [13]. In 2018, building on their progress, ICON partnered with the nonprofit organization New Story to achieve a significant breakthrough. This collaboration led to the introduction of the first legally approved 3D-printed houses in the United States, addressing the critical issue of affordable housing solutions.

The construction of these pioneering houses utilized ICON's specially designed Vulcan printer, created specifically for construction purposes, with a focus on constructing large-scale structures such as buildings. In essence, the Vulcan printer represents a specialized advancement tailored to the unique requirements of the construction industry, whereas a standard 3D printer serves a diverse range of applications across various sectors. This printer is tailored to deposit construction-grade materials and is capable of constructing entire walls and structural elements, working with materials like concrete, mortar, or other suitable compounds that provide the required strength and durability for building structures. This accomplishment exemplifies the ongoing innovation within the 3D printing field, to address housing challenges and offer affordable solutions, while also significantly reducing construction time and minimizing material waste [14].

Use of plastics in 3d printing and alternative materials. Additive manufacturing, recognized for its inherent waste reduction capabilities, has been acknowledged as an environmentally friendly process. This dedication to sustainability is exemplified by influential additive manufacturing leaders' increased involvement in the Additive Manufacturer Green Trade Association (AMGTA) [15, 16].
As 3D printing gains traction across industries, its environmental impact, particularly regarding plastic usage, has become a topic of scientific inquiry. While 3D printing offers benefits like customization and waste reduction compared to traditional manufacturing, concerns have been raised about the ecological implications of plastic materials involved.
An integral facet presently under scholarly examination pertains to the life cycle assessment (LCA) of plastics employed within the domain of 3D printing. LCA methodologies furnish an encompassing evaluation of the ecological footprint associated with a product, traversing the entirety of its life cycle - starting from the procurement of raw materials to eventual disposal. Diverse inquiries have delved into pivotal considerations such as energy consumption, emissions of greenhouse gases, and various other environmental indicators intricately intertwined with the landscape of 3D printing processes involving plastic substrates.
Kreiger and Pearce (2015) conducted an LCA comparing the environmental impacts of distributed 3D printing and conventional manufacturing of polymer products [17]. Their findings revealed that while 3D printing reduces material waste, it often leads to higher energy consumption and emissions due to the energy-intensive nature of the process. This highlights the need for further research and development to optimize the environmental performance of 3D printing concerning plastic materials.
The environmental implications of plastic usage in 3D printing are intricately tied to the selection of specific plastic materials. Some types of plastics, such as polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS), possess unique properties and exhibit distinct environmental footprints. Thoroughly considering the extraction, production, and disposal processes of plastic feedstocks, alongside a comprehensive understanding of the life cycle impacts of the plastics employed in 3D printing, constitutes the cornerstone for informed decision-making and the cultivation of sustainable practices [18]. Concerted efforts are currently underway to address the environmental repercussions of plastic usage in 3D printing.

Alternative materials in 3D Printing and Integration of Computational Design. Researchers and stakeholders in the industry are actively exploring alternative materials endowed with improved environmental characteristics, particularly focusing on bio-based and biodegradable polymers (Fig. 2) [19]. Speck et al. (2017) investigated the use of 3D printing to fabricate lightweight bio-inspired structures that mimic the strength and efficiency of natural materials, with the aim to reduce material waste and energy consumption in the construction process [20].

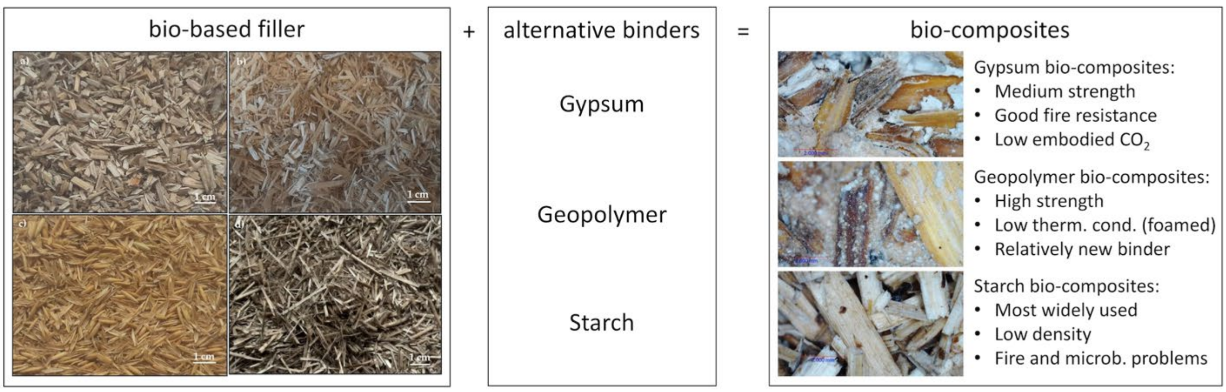

Fig. 2. Bio-based filler, alternative binders and bio-composites.

Naboni et al. (2019) conducted a research project based on a multi-scale computational workflow that integrates several aspects, such as material testing, bio-inspired design algorithms, multi-criteria optimization and production management. Furthermore, they underscored the significance of encompassing both environmental and economic aspects through life cycle assessments and costing analyses of 3D printing technology [21]. Their exemplar project is represented by Trabeculae Pavilion, inspired by the intricate composition of trabecular bone. This load-responsive avant-garde structure represents the fusion of cutting-edge Additive Manufacturing techniques with the creative principles of bio-inspired computational design. The lattice structure, characterized by its interconnected network of slender elements, mimics the porous arrangement found in natural bone tissues. This architectural interpretation of nature's ingenuity not only exudes visual elegance but also serves as a testament to the Pavilion's commitment to sustainable design, using Fused Filament Fabrication (FFF) one of the most cost-effective additive techniques of production.

The lattice's inherent lightweight nature minimizes the need for excessive construction materials, translating into reduced environmental impact and enhanced structural efficiency. The experiment is very interesting because it can demonstrate the possibility of realizing structures according to various scales precisely because the Trabeculae Pavilion design process involves material and structural optimization algorithms on multiple and interdependent hierarchical levels [22]. Every scale is intricately correlated with the others through considerations of form, materials and performance principles, leading to the evolution of a computational process. This workflow integrates diverse algorithms of varying types to facilitate the development of a unified and harmonious multi-scale design.

Fig. 3. Trabeculae Pavilion installed at Politecnico di Milano campus. Courtesy of Gabriele Seghizzi

In parallel, other initiatives are being formulated to establish recycling and waste management systems that are specially tailored to address the materials used in 3D printing. Closed-loop systems, designed to facilitate the collection and reprocessing of plastic waste derived from 3D printing, can effectively minimize the environmental impact, harmonizing with the principles of the circular economy [23].

In the early 2020s, other research has explored alternatives to traditional concrete, such as geopolymers and bio-based composites, to fabricate structures characterized by both lightweight attributes and remarkable strength, thereby manifesting a noteworthy reduction in carbon emissions [24] (Fig. 5). These efforts respond harmoniously to the surging demand for sustainable construction practices and the imperative to diminish the ecological impact of the industry. In fact, geopolymers are a class of materials that offer several advantages for 3D printing, including high early strength, fire resistance and lower carbon emissions compared to traditional cement-based materials [25]. In summary, it is possible to develop structurally sound and sustainable building components. On the other hand, bio-based composites represent a promising avenue in material science, wherein natural substances obtained from replenishable sources, such as natural fibers (Fig. 4) or biopolymers (Fig. 5) are employed as reinforcing agents within a matrix material.

Natural Fibres	Natural Plant or Vegetable (Cellulose or Lignocellulose)	Seed	Cotton, Kapok, Milkweed
		Bast or Stem	Flax, Hemp, Jute, Ramie, Kenaf
		Leaf or Hard	Pineapple (PALF), Banana (Abaca/ Manila-hemp), Henequen, Sisal
		Stalk	Wheat, Maize, Barley, Rye, Oat, Rice (Husk)
		Cane, Grass & Reed Fibres	Bamboo, Bagasse, Esparto, Sabei, Phragmites, Communis
		Fruit	Coir or Coconut Fibres
	Animal (Protein)	Wool/Hair	Lamb's Wool, Goat Hair, Angora Wool, Cashmere, Yak, Horse Hair
		Silk	Tussah Silk, Mulberry Silk
	Mineral Fibres	Asbestos Fibrous brucite Wollastonite	

Fig. 4. Natural fibers classification

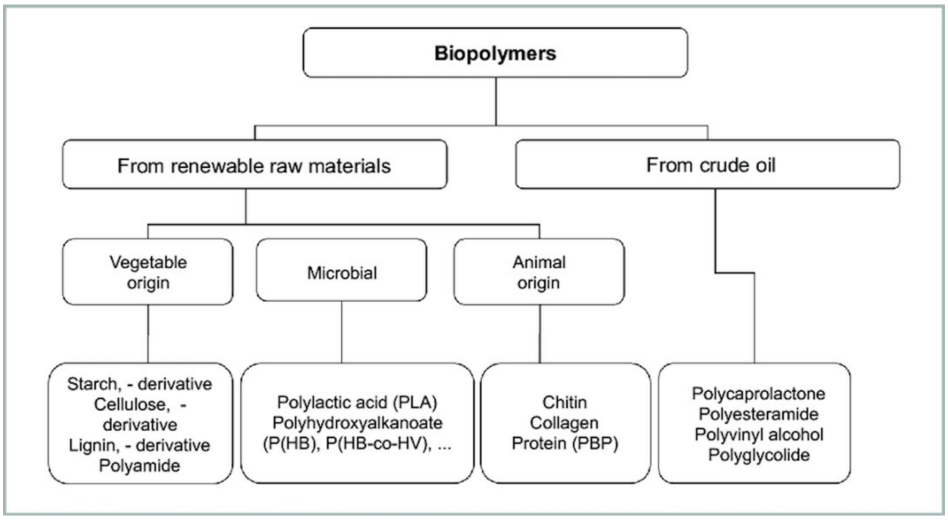

Fig. 5. Biopolymers classification

Robotic and Automation Technologies. Contemporary research is focusing on enhancing the efficiency and precision of 3D printing processes for housing construction through the integration of robotics and improving the potential of on-site assembly [26]. Collaborative research endeavors between robotics engineers, computer scientists, and architects are yielding breakthroughs in real-time monitoring, adaptive printing, and autonomous robotic construction systems.

A notable study by Peng et al. (2018) explored the use of contour crafting and large-scale robotic arms for constructing building facades. Their research was focused on integrating architectural and functional requirements in the fabrication of facade elements using 3D printing technology. By enabling customization and design optimization, they investigated the creation of high-performing facade designs with enhanced functionality [27]. An important contribution in this field comes from Neri Oxman, an architect, designer, and professor at the MIT Media Lab. Her research group, Mediated Matter, focuses on the intersection of design, biology and material science. One of the projects undertaken by Mediated Matter is Fiberbots, which serves as a platform for digitally designing and fabricating large-scale structures with high spatial resolution [28]. Fiberbot works with fiber-reinforced composite materials like carbon fiber and fiberglass, aiming to fashion lightweight, robust, and adaptable building components (Fig. 6).

Specifically, it utilizes a robotic system to achieve precise and adjustable positioning of the fibers, integrating them into a structural matrix to form cohesive and functional elements. This innovative approach involves a coordinated swarm of mobile robotic units, also known as robots, governed by computational algorithms, to position and combine fibers, resulting in selected structural shapes [29]. The ultimate objective is to facilitate the fabrication of load-bearing structures with intricate geometries that optimize material usage and enhance structural performance, also contributing to the enhanced scalability of 3D printed housing solutions.

Fig. 6. Swarm of Fiberbots and details

On-site 3D printing, multi-material printing and the integration of sensors for structural health monitoring in 3D-printed buildings. Recent trends include projects for on-site 3D printing, multi-material printing, and the integration of sensors for structural health monitoring in 3D-printed buildings [30].

On-site 3D printing has emerged as a disruptive technology in the construction industry, enabling the fabrication of building components or entire structures at the construction site. This approach offers many advantages over traditional construction methods, one of which is a significant saving in time and costs. As a matter of fact, on-site 3D printing eliminates the need for complex and time-consuming transportation of prefabricated components, reducing labor costs and construction time. This efficiency translates into reduced labor costs and faster project completion, which can have a substantial impact on overall project budgets and timelines.

Furthermore, on-site 3D printing enables a high level of customization and adaptability during the construction process. Traditional construction methods often require extensive planning and fabrication of components based on predetermined specifications. In contrast, on-site 3D printing allows for real-time adjustments and changes to be made during the printing process itself. This flexibility allows architects and planners to experiment with different designs, iterate quickly, and adapt to specific site conditions. This method also provides the basis for adaptive construction, where buildings can be modified or expanded easily in response to changing needs or future developments. Riyadh, Saudi Arabia, renowned as home to the tallest building in the world, is predictably asserting its dominance with the world's most extensive 3D printed construction, at least for now. In this effort, the city has enlisted the expertise of Saudi Arabia's leading real estate developer, Dar Al Arkan, using a COBOD 3D construction printer (Fig. 7). Dar Al Arkan launched its pioneering 3D Concrete Printing (3DCP) technology in the fourth quarter of 2021. This strategic move underscores the company's leadership in driving the transition of the construction and real estate sector towards advanced and sustainable building practices. This initiative aligns with the goals of Saudi Vision 2030, a national initiative aiming to support economic diversification and digitalization, making strides towards a progressive future.

Fig. 7. Riyadh, Saudi Arabia. The tallest 3d printed building in the world

Multi-material printing represents another promising frontier for innovation within the realm of 3D printed construction. Traditional construction methods often rely on a diverse range of materials, each chosen for specific structural attributes and aesthetic qualities. The concept of multi-material printing facilitates the fusion of different materials during a single 3D printing process, thereby enabling a convergence of distinct functionalities. To illustrate, reinforcements like fibers and metals can be integrated into the printed components, imparting heightened strength and durability. Furthermore, elements such as thermal insulation and acoustics can be directly incorporated into the printed structure, obviating the requirement for subsequent installation steps [31]. In a ground-breaking stride, the Wyeth Institute at Harvard University has introduced the concept of multi-material multi-nozzle 3D (MM 3D printing). This revolutionary technology permits the transition between up to eight diverse materials within a single nozzle, mirroring the fluid adaptability witnessed in natural plant movement. This innovation aims to sculpt architecture capable of metamorphosis, inspired by the inherent flexibility of the natural plants [32]. Another active research area centers around the integration of distributed carbon nanotube composite sensors for monitoring the structural integrity of 3D-printed concrete. The unique electrical properties of the carbon nanotubes make them highly apt for sensor applications. Embedding these sensors within 3D-printed concrete structures empowers the continuous monitoring of an array of parameters, including strain, cracks, temperature, and humidity. This integration affords real-time insights into the structural integrity and performance of the concrete, providing real-time feedback on structural integrity and performance [33].

Discussion

Advancement in building sectors: Disaster-Resistant and Resilient Housing

Gaia. The progress of 3D printing technology in recent years has led to its growing prominence within the architectural sector, particularly in the creation of new building typologies, characterized by sustainability and resource efficiency. During the “A call to save the world” Conference, specifically the event “Journey to Shamballa” in 2018, WASP (World’s Advanced Savings Project), a leading company in the 3D construction sector specializing in low-cost prototyping, unveiled Gaia, the world’s first-ever building constructed using local raw earth and other natural compounds. The circular housing prototype was erected in a remarkably swift timeframe of just 200 hours, utilizing multiple 3D printers [34].

The successful completion of this construction project within a relatively short period of just over two weeks serves as compelling evidence of the potential of 3D printing technology in rapidly and efficiently creating affordable housing solutions. The design of the house is meticulously optimized for energy efficiency, featuring a passive solar technology that maximizes the utilization of natural light and ventilation. Additionally, the circular shape of the structure minimizes heat loss, contributing to a comfortable living environment for the occupants.

A noteworthy innovation incorporated into the Gaia structure is the implementation of a *living wall* system, aimed at enhancing the indoor air quality within the house. This system entails the vertical growth of a series of plants on the exterior facade that actively contribute to air purification by filtering out pollutants, thereby improving the overall health and well-being of the occupants [35]. Further, the integration of digital software and design presents a compelling avenue for exploring the diverse capabilities of 3D technology in harnessing agricultural resources on a global scale. This approach not only enables efficient resource utilization but also ensures minimal environmental impact. Leveraging the infinite design possibilities afforded by 3D printing is of paramount importance in advancing sustainable living and pushing the boundaries of agricultural practices into various contexts.

A notable advantage of 3D printing lies in the ability to fabricate structures capable of withstanding natural disasters and adapting to changing environmental conditions [36]. In fact, through complex geometries and the integration of smart materials, these technologies have showcased impressive resilience against seismic activities, hurricanes and floods, leading to the creation of robust and disaster-resistant housing solutions. The application of 3D printing technology in the construction industry has garnered significant attention in the way of addressing the worldwide housing crisis, especially in the context of the COVID-19 pandemic [37].

The pandemic has exacerbated the housing situation, resulting in heightened financial struggles for many individuals due to job losses and reduced income [38]. In the post-pandemic recovery phase, the industrialization of the 3D printing industry, especially in large-format and large-scale product printing, has significantly increased. This trend aligns with the growing focus on resilient and disaster-resistant housing design, driven by the need for efficient and expedient construction methods [39]. According to projections by the United Nations Habitat, approximately three billion people, which accounts for about 40% of the global population, will require access to adequate housing by the year 2030 [40]. This projection underscores the urgent and immense challenge in addressing the global housing crisis, emphasizing the need for innovative and efficient approaches like 3D printing technology to meet this unprecedented demand. Before the COVID-19 pandemic, the use of 3D printing in housing and shelter construction was limited [41].

Tecla. In Italy, the Tecla project, a collaboration between Mario Cucinella Architects and WASP (World's Advanced Saving Project), is garnering attention as a pioneering effort in sustainable 3D printed housing that could have implications in the post-pandemic world (Figs. 8, 9). Actually, the project's emphasis on sustainable, eco-friendly construction could align with the growing demand for healthier and environmentally conscious living spaces post-pandemic.

Developed in 2021, Tecla is the world's first fully 3D-printed residential dwelling realized entirely with eco-friendly materials. Representing a best practice in sustainable and affordable housing, it exemplifies how energy demands and construction costs can be reduced while prioritizing environmental concerns [42]. The structure is mainly composed of a sustainable composite material that combines rice husk with a mixture of natural fibers like bamboo or straw. This composite material is bound together using a binder, which can be a bio-based resin or another eco-friendly adhesive. The combination of rice husk, natural fibers and a binder creates a strong and durable material that provides structural integrity to the structure.

The integration of rice husk and natural fibers, like bamboo or straw into the composit material, enhances the material's environmental profile by providing a renewable and eco-friendly alternative to traditional building materials with a lower carbon footprint. Rice husk, an abundant agricultural waste product, becomes a valuable resource when utilized as a key component in creating a biodegradable composite material, reducing waste and promoting resource efficiency.

The innovative use of rice husk in Tecla's material composition significantly contributes to its exceptional mechanical strength, elevating the durability and stability of the structure. About the shape, the organic and curvilinear architectural design of Tecla, inspired by the grace of natural forms, allows for adaptation to the intricate morphology of the surrounding terrain [43]. This approach involves mimicking the contours found in nature, integrating flowing lines, harmonizing with natural elements, optimizing views and natural light and facilitating efficient natural ventilation, all of which culminate in a design that harmoniously merges the structure with its environment.

The adaptation to the intricate morphology of the surrounding terrain goes beyond visual harmony. The design integrates practical considerations as well. By conforming to the natural contours, the curvilinear design allows for efficient spatial utilization and smooth circulation within the building.

In addition, the smooth and flowing lines of the structure facilitate the capture and distribution of daylight, reducing the need for artificial lighting during the day. The curved surfaces also facilitate airflow direction, optimizing natural ventilation. The absence of sharp corners minimizes wasted space, fostering a sense of continuity and fluidity. This synthesis of form and function heightens the dwelling's usability and comfort, promoting energy efficiency and sustainable living.

To further enhance sustainability, Tecla integrates systems to reduce the reliance on traditional resources while simultaneously minimizing the environmental footprint: [44]

Rainwater Harvesting Systems. The architectural design incorporates strategically positioned gutters, downspouts and collection channels to efficiently capture and channel rainwater. The collected rainwater is directed towards storage tanks or reservoirs, typically located underground or integrated within the building's structure. Prior to usage, the collected rainwater undergoes thorough filtration and treatment processes to ensure its quality and suitability for purposes such as irrigation, toilet flushing and laundry.

Solar Energy Production Technologies. The structure embraces solar energy as a primary renewable energy source. The design of the dwelling incorporates solar panels on the roof and façade, employing photovoltaic (PV) technology to harness sunlight and convert it into electricity. The placement of these solar panels is carefully planned to optimize solar exposure and maximize energy generation. The captured solar energy is then either stored in batteries for later use or directly fed into the building's electrical system. This solar energy powers a range of functions within the house, such as lighting, appliances and other electrical devices. By making extensive use of solar energy, Tecla reduces reliance on fossil fuels, mitigates greenhouse gas emissions linked to conventional energy sources and contributes to a low-carbon energy supply.

Smart Energy Management Systems. The house incorporates intelligent energy management systems that monitor energy consumption, optimize usage patterns and prioritize energy distribution. These systems help minimize energy waste and promote efficient utilization of available resources. Additionally, energy storage solutions may be employed to ensure a consistent and sustainable power supply, even during periods of limited sunlight. By integrating these smart energy management systems, Tecla enhances energy efficiency and improves the effective use of solar energy, further reducing the general environmental impact of the structure.

The methodology emphasizes the importance of affordability, seeking to face the persistent housing crisis, providing solutions that are accessible and economically viable. Tecla also recognizes the significance of social inclusivity, aiming to create communities that foster equity, diversity and well-being, furthering the cause of an environmentally conscious development on a broader scale.

Finally, Tecla is an ambitious example of a forward-thinking initiative that addresses sustainability, adaptability and efficiency - all considerations that gained prominence due to the pandemic's effects on how we live and work. While it might not be a direct response to the pandemic, it serves as a notable example of a good practice of how 3D printed housing can align with the evolving needs of a post-pandemic world.

Figs. 8. 9. TECLA by Mario Cucinella in collaboration with WASP. View of On-site 3D printing in Massa Lombarda, province of Ravenna, Italy

Contemporary research and 3D printed houses after the pandemic. Contemporary research is at the forefront of developing specific materials for 3D printed houses. The exploration of sustainable alternatives to traditional construction materials has led to the formulation of eco-friendly concrete mixes, biodegradable polymers and even construction-grade natural fibers. Collaborative research efforts are dedicated to optimizing these materials for 3D printing, in order to meet structural, thermal and durability requirements while minimizing environmental impact.

In 2018, a collaborative project involving IIT Madras faculty members and the Chennai-based startup Tvasta resulted in the swift construction of a house on the university campus in just about a week. This compact abode, spanning 32 square meters, was thoughtfully designed for optimal efficiency, resulting in a 30% cost reduction and a significant reduction in waste generated during the construction process [45]. This accomplishment was bolstered by a strategic shift away from manual labor, accompanied by the integration of recyclable and versatile materials. These deliberate choices not only enhanced the economic viability of the dwelling but also contributed substantially to the mitigation of its environmental impact.

Continuing their trajectory of achievement from previous undertakings, the Tvasta team achieved another milestone in 2020 by erecting a dwelling spanning 56 square meters within the confines of IIT Madras. The structural robustness of their 3D-printed concrete can be achieved within a few minutes and the entire edifice can be completed in just a week (Fig. 10) [46].

This feat of engineering represents a substantial leap forward in the endeavor to provide secure, cost-effective housing solutions for vulnerable communities worldwide [47]. By exemplifying the potential of 3D printing technology in the construction sector, Tvasta's achievements underscore the prospects of innovative building methods to address global housing needs, while simultaneously mitigating financial strain and providing environmental benefits.

Fig. 10. Tvasta's first structure is a single-storey house, a 600-sq ft unit, created in collaboration with Habitat for Humanity's Terwilliger Center for Innovation in Shelter at the IIT-Madras campus.

Project Milestone, a collaborative endeavor involving Eindhoven University of Technology, Van Wijnen, Saint-Gobain Weber Beamix and other partners, stands as an inspiring exemplar of 3D printing technology's significant impact on the construction industry and housing sector (Fig. 11). The project's ambitious aim entails the design and construction of five 3D-printed houses, specifically intended for family habitation, with a foreseen minimum projected lifespan of 50 years. [48].

The first house, completed in 2019, marks European achievement as the first legally habitable 3D-printed dwelling. This striking single-story bungalow boasts a graceful, curved design, comprising two bedrooms and a living area of 94 square meters. Employing concrete printing, a specialized variant of 3D printing, the construction process imbued the house with an organically flowing form, gracing its walls with unique textures. In fact, the large-scale 3D printer meticulously deposited concrete material layer by layer, resulting in the precise realization of the architectural design. Such innovative construction techniques facilitated the efficient production of visually appealing components, which were seamlessly assembled on-site to complete the final structure [49].

These robust walls, an impressive 11 centimeters thick, ensure both structural integrity and optimal thermal performance. The integration of pipes and ducts for electricity and plumbing directly into the 3D-printed walls during the concrete printing process streamlined the installation of these vital components. This approach bypassed the need for separate installation procedures, significantly reducing construction time and enhancing overall efficiency.

The successful completion and habitation of the 3D-printed houses in Project Milestone signify a noteworthy advancement in the progressive evolution of 3D printing technology within the construction industry. In this context, the achievement accentuates the practical viability and inherent environmental responsibility in constructing both functional and aesthetically pleasing residences.

With an innovative approach that integrates sustainable design principles and streamlines construction timelines, the distinct design of the house is a product of extensive research and development endeavors aimed at unlocking the design freedom of concrete printing.

The achievements highlight the transformative potential of 3D printing technology in a framework of responsible construction practices, demonstrating the ability to address housing challenges on a global scale in order to meet the diverse needs of various communities.

Fig. 11. Eindhoven: A 3D-Printed Concrete House within the Project Milestone Framework

Additive manufacturing for solving housing's crisis in South Africa. South Africa is facing a significant shortage of affordable housing, exacerbated by rapid urbanization, population growth and limited resources [50].

In 2021, a collaborative study by the Academy of Science of South Africa (Assaf) and the Department of Science and Innovation (DSI) unveiled a substantial urban housing backlog, surpassing 2.4 million houses. This situation has forced numerous families into informal settlements [51]. As a strategic response to the housing crisis in South Africa, the University of Johannesburg made a significant investment in 3D printing technology during 2022. This initiative aims to effectively tackle the social housing backlog prevailing in the country. Projections indicate that the 3D printing market is poised to reach a substantial valuation of $40 billion by 2024.

Indeed, over the years, research and experimentation with various typologies of 3D-printable materials have expanded significantly, rendering the technology increasingly valuable across diverse sectors. Notably, the 3D printer deployed at the University of Johannesburg holds the capacity to construct an entire cost-effective house within 8 hours. More specifically, the resulting building presents upgraded features in comparison to conventional housing structures, encompassing heightened strength, enhanced fire resistance and improved insulation properties (Figs. 12, 13) [52].

While the integration of 3D printing presents a promising and sustainable solution to the housing crisis in South Africa, it is essential to recognize the multifaceted nature of the housing challenge. The Constitutional Court, in the case of Government of the Republic of South Africa and Others v Grootboom and Others, eloquently articulated that the concept of housing transcends mere construction materials, encapsulating a comprehensive framework encompassing land availability, essential services such as water provisioning and sewage management and the financial means to support these components, including the actual construction of the dwelling itself. Indeed, to ensure the realization of adequate housing, a holistic approach is necessary, addressing not only issues about the physical structure but also the elements of land accessibility and service provision availability.

As established by legal precedent, access to land stands as an inherent component of the right to adequate housing, reaffirming the interconnectedness of these elements within the broader context of housing rights [53]. Implementing the advancement of 3D printing technologies requires a concerted effort in upskilling architects and engineers. Indeed, as emerging roles, opportunities, and industries take shape, the need to align skills, automation, and employment becomes ever more pronounced.

Embracing a proactive approach to these advancements is crucial for bridging the skills gap and adapting to the evolving landscape. Traditional construction methods struggle to keep up with the demand, leading to inadequate living conditions for a significant number of citizens.

Therefore, the housing crisis requires solutions that can be scaled rapidly and additive manufacturing technology offers the potential for mass production of housing units in a short period. By reproducing designs and harnessing automated processes, 3D printing has the potential to substantially amplify housing unit production, thereby addressing the housing crisis in South Africa and benefiting a greater number of people in need [54].

The potential to construct affordable, customizable and sustainable buildings gives a glimpse into the future of construction sector in sensitive contexts. Furthermore, through the strategic use of this technology, South Africa can make substantial progress in offering its citizens dignified and secure housing. This effort can contribute to enhanced living conditions and the advancement of community development.

To introduce 3D printing as a compulsory subject in all high technical schools and Technical Vocational Education and Training institutes (Tvet) is a good practice. The successful implementation of the mandatory AI literacy course at the University of Johannesburg serves as an exemplary illustration of how this strategy can be effectively executed.

Developing national plans for reindustrialization catalyzed by 3D printing and investing in 3D printing facilities and, through tax breaks, can incentivize companies to invest in this technology to increase productivity, as well. In the face of vast inequality and a housing crisis, tangible solutions cannot be dismissed because the opportunities exist. Therefore, the wider implications need to be examined as these changes and their potential impact are addressed.

Fig. 12. South Africa's first 3D printed low-cost house.

Fig. 13. South Africa's first 3D printed low-cost house

Conclusions

Future challenges and prospects

The findings of this contribution demonstrate an ever-increasing development of the building and design industry through 3D printing technology. In recent decades, alternative high-performing materials created by innovative printing systems is changing the way of doing architecture. Collaborative endeavors are indispensable for pushing the boundaries of material efficiency in 3D printing applications. By adopting a collaborative and multidisciplinary approach, architects, material scientists and engineers can develop the best strategies and materials tailored to meet the specifications of 3D printing techniques. This synergy ensures that material properties are optimized not only for structural integrity but also for eco-consciousness, promoting the responsible utilization of resources and reducing the reliance on traditional building materials known for their environmental impact. However, it is necessary to address several challenges to gain widespread adoption in the construction industry.

A primary challenge revolves around the need for standardized regulations and building codes specifically designed to address the complexities of 3D printing. Prevailing codes oftentimes inadequately encompass the distinct facets of additive manufacturing, encompassing material characteristics, construction techniques and quality validation. As the tide surges towards heightened adoption of additive manufacturing in construction endeavors, the inadequacies of extant building codes are manifest.

Continuously evolving guidelines, precisely calibrated to accommodate the unique characteristics of 3D printing systems, are consistently refined to ensure the sustained safety and compliance within the construction sector. These regulations encompass considerations, including structural robustness, ecological ramifications, legal ramifications and construction benchmarks.

Another significant challenge is the scalability of 3D printing technologies. While miniature-scale prototypes have successfully materialized, transmuting these paradigms to erect more expansive and intricate edifices mandates strides in print celerity, automation, and the evolution of monumental-scale printers. Finally, another issue is the cost-effectiveness of 3D. While these technologies can reduce construction costs over the long term, initial investment costs can be significant. For that reason, it is important to identify locally available material, recommend the most appropriate one available for local 3d printing.

Finding ways to optimize the printing process, reduce material expenses and increase production efficiency will be crucial to making 3D printing economically viable for mainstream construction projects.

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