Informes de la Construcción 76, (574)
abril-junio 2024, 6627
ISSN-L: 0020-0883, eISSN: 1988-3234
https://doi.org/10.3989/ic.6627

3D constructing: Exploring the potential of 3D concrete and clay printing with generative design for architectural innovation

Construcción 3D: Explorando el potencial de la impresión 3D de hormigón y arcilla con diseño generativo para la innovación arquitectónica

Javier Alonso Madrid ATANGA Arquitectura e Ingeniería. Spain. javier@alonsomadrid.com (autor de contacto)
Guillermo Sotorrío Ortega Eduardo Torroja Institute Construction Science, Spanish National Research Council (CSIC). Spain. sotorrio@ietcc.csic.es
Nils O.E. Olsson Norwegian University of Science and Technology. Norway. nils.olsson@ntnu.no
José Antonio Tenorio Río Eduardo Torroja Institute Construction Science, Spanish National Research Council (CSIC). Spain. tenorio@ietcc.csic

ABSTRACT

The architectural and construction sectors are experiencing a transformative shift with the advent of 3D constructing. This research delves into the potential of 3D printing technologies when combined with generative design principles to reshape traditional construction methods. Through a comprehensive lens, the study evaluates the generative design workflow, decision-making algorithms, machines capacities and material considerations. Results indicate that, when synergized with generative design, these technologies offer sustainable, efficient, and tailored solutions. The use of accesible materials, such as clay and cement, demonstrates their superiority over conventional alternatives. However, the challenge lies in harmoniously integrating these innovations into architectural practice, ensuring a balance between cutting-edge advancements and practical application. Conclusively, this new approach heralds a future of sustainable and user-centric design, but its full potential can only be tapped with a holistic strategy that encompasses both design and material facets.

Keywords*: 3D constructing, 3D claying; 3DCP, 3D printing; additive manufacturing; carbon print; generative design; topologicainability.*

RESUMEN

Los sectores de la arquitectura y la construcción están experimentando un cambio transformador con la llegada de la construcción en 3D. Esta investigación profundiza en el potencial de las tecnologías de impresión 3D combinado con los principios de diseño generativo para remodelar los métodos constructivos tradicionales. El estudio evalúa el flujo de trabajo del diseño generativo, los algoritmos de toma de decisiones, las capacidades de las máquinas y las consideraciones de materiales. Los resultados indican que estas tecnologías combinadas ofrecen soluciones sostenibles, eficientes y personalizadas. El uso de materiales accesibles, como la arcilla y el cemento, demuestra su superioridad sobre las alternativas convencionales. El desafío radica en integrar armoniosamente estas innovaciones, asegurando un equilibrio entre la vanguardia y la práctica. Este nuevo enfoque anuncia un futuro de diseño sostenible y para el usuario, pero su potencial solo puede aprovecharse con una estrategia holística que abarque el diseño y los materiales.

Palabras clave: 3D constructing, 3D claying; 3DCP, 3D printing; fabricación aditiva; huella de carbono; diseño generativo; optimización topológica; fabricación digital; sostenibilidad.

Cómo citar este artículo/Citation: Javier Alonso Madrid, Guillermo Sotorrío Ortega, Nils O.E. Olsson, José Antonio Tenorio Ríos (2024). 3D constructing: Exploring the potential of 3D concrete and clay printing with generative design for architectural innovation. Informes de la Construcción, 76(574): 6627. https://doi.org/10.3989/ic.6627

Recibido/*Received*: 06/11/2023
Aceptado/*Accepted*: 07/05/2024
Publicado on-line/*Published on-line*: 01/10/2024

1. INTRODUCTION

1.1. Background and motivation

Based on previous research works in the domain of 3D printing with clay and concrete in architecture, as "3D Claying: 3D Printing and Recycling Clay" (1), "Printability of materials for extrusion 3D printing technologies: a review of material requirements and testing" (2), "Industry 4.0 in a project context: Introducing 3D printing in construction projects" (3), "Concrete hybrid manufacturing: A machine architecture" (4), and "Life cycle assessment of integrated additive–subtractive concrete 3D printing" (5), it can be established a foundational understanding of the benefits and challenges of ultra-high performance clay and concrete 3D printing in terms of sustainability and efficiency in construction.

In this study, building upon our previous investigations and the insights from Rahmat (6) on sustainable concrete and Robayo-Salazar (7) on hybrid cements, we aim to further the boundaries of clay and concrete 3D printing. It also can be considered interesting about the integration of generative design techniques, as discussed by Gradišar (8), topological optimization, highlighted by Szabó (9), and other parametric design techniques. Our overarching goal is to harness these methodologies to enhance customization, structural efficiency, and aesthetics in sustainable architecture.

Our focus will be on the development and integration of generative design algorithms specifically tailored for mud and cement 3D printing, inspired by the work of Kromer and Gruhier (10). These algorithms will facilitate the automated generation of intricate shapes and structures, optimized to fulfill the structural and functional prerequisites of architectural projects.

3D printing with clay and concrete, known as 3D Claying and 3DCP respectively, represent emerging techniques in the field of additive manufacturing. These techniques facilitate the creation of three-dimensional structures and objects using clay, concrete, or other ceramic materials. Such advancements have garnered significant attention in the architectural industry due to the efficient generation of intricate and customized shapes.

The initial segment of this section focuses on 3D printing with clay and concrete, based on layering techniques distinct from methods like plastic extrusion, requiring careful consideration of material properties such as viscosity and moisture. Specialized extruders and robotic systems are employed for precision and large-scale printing. Additionally, generative design is discussed for its role in optimizing designs for material and structural efficiency in 3D printing with these materials.

2. DEFINITIONS

We can consider several definitions that are important for this work.

3D Claying focuses on the utilization of clay or ceramic materials. This method capitalizes on clay's natural properties, which have been revered in construction for centuries. With 3D Claying, structures benefit from enhanced insulation, ecological sustainability, and a distinctive aesthetic appeal. The process involves the meticulous preparation of clay, ensuring optimal consistency for the printers. These advanced machines then methodically deposit layers of the clay mixture, materializing the digital design. Once print-ed, the structures undergo a drying process, and can, if required, be kiln-fired for added resilience, but without this process, its reuse is almost infinite and can be considered that its carbon footprints is null.

3D Concrete Printing (3DCP), on the other hand, employs concrete as its primary material. Concrete's inherent strength and versatility make it an ideal candidate for this printing method. 3DCP transcends the mere act of replacing traditional concrete pouring. It rejuvenates the material's potential, allowing for the creation of structures without the need for molds or formworks. This precision-driven technique not only curtails material waste but also expands the design horizon, enabling architects to envision and craft previously inconceivable structures.

Generative design represents a paradigm shift in the approach to architectural and engineering design processes. Far from the conventional methods where designers and architects manually draft each iteration, generative design leverages the computational power of modern software to produce design variations based on predefined criteria and constraints.

At its core, generative design is an algorithm-driven process. Designers input specific criteria, such as material types, structural requirements, environmental factors, and aesthetic preferences. The software then takes these inputs and, through iterative algorithms, generates a myriad of design possibilities that satisfy the given conditions. The result is a vast design space where each solution is optimized for the defined parameters, allowing stakeholders to choose an outcome that best aligns with their vision and objectives.

Just as GD uses algorithms to generate multiple design solutions, the concept map encourages learners to actively integrate new information with existing knowledge. Organized hierarchically, the map features nodes for key concepts, links for relationships, and cross-links for interconnections. This dynamic tool not only promotes critical thinking and adaptability but also mirrors the iterative nature of GD, emphasizing the importance of active engagement in both design and learning processes.

Parametric modeling stands at the intersection of design, mathematics, and technology, offering a dynamic approach to architectural and engineering design. This method, rather than defining design elements explicitly and statically, assigns relationships and algorithms to components, allowing them to adapt and evolve based on changes to predefined parameters.

The core principle of parametric modeling is the establishment of relationships between design elements. For instance, the height of a structure might be defined as a function of its width or the angle of a window's tilt might be related to its exposure to sunlight. By manipulating these parameters, designers can witness an instantaneous and automatic adjustment of the entire model, ensuring that the overarching design logic remains consistent.

In relation to the previous definitions, and as a novel contribution,"3D Constructing" can be defined as a transformative approach within the construction industry, blending the precision and versatility of additive manufacturing, or 3D printing, with traditional construction methods. This innovative technique is redefining architectural and structural design, bringing forth an era where digital designs seamlessly transition into tangible structures.

At the heart of 3D Constructing lies the potential to realize intricate designs, previously deemed unattainable due to the limitations of conventional construction. This methodology facilitates rapid prototyping and building, with a stark reduction in material wastage and an increase in design accuracy. The adaptability of 3D printing techniques to construction ensures a broader design scope, allowing architects and engineers to push the boundaries of creativity.

3. LITERATURE REVIEW

3.1. Additive manufacturing in architecture

Additive manufacturing, commonly known as 3D printing, has revolutionized the way structures are designed, developed, and built in architecture. This technology enables the creation of complex components and structures by adding material layer by layer, offering unprecedented flexibility in design and manufacturing.

Architecture has traditionally been a discipline that relies on building from prefabricated components or standard materials. However, with the advent of 3D printing, architects now have the ability to design and build structures that were previously unthinkable or extremely difficult to realize with traditional methods. Bañón and Raspall (11) highlight how 3D printing has enabled the creation of architectural structures that are not only aesthetically appealing, but also functional and efficient.

With 3D printing, structures can be specifically designed to adapt to the environment in which they are located, taking into account factors such as climate, topography and the specific needs of the client, highlighting the importance of customization and adaptability offered by this technology (12).

In addition, 3D printing in construction is not limited to traditional materials such as concrete or steel. Alqenaee, Memari and Hojati have researched the transition from traditional construction to 3D printing clay houses, demonstrating the versatility of the technology (13). Chen has also researched how calcined clay-based materials can be used for sustainable concrete 3D printing (14).

The integration of 3D printing with Industry 4.0 methodology has led to significant advances in construction. Darwish, El-Wakad and Farag discuss how Industry 4.0, with its focus on automation and interconnection, can be used to create a real-time programming architecture for distributed 3D printing services (15). This integration allows for greater efficiency, reducing construction time and cost.

However, the adoption of 3D printing in architecture is not without its challenges. Training and education are essential to ensure that architects and builders are familiar with new technologies and techniques. In addition, continuous research and development is crucial to overcome current limitations and expand the possibilities of 3D printing in construction. For all these reasons, we can say that 3D printing is redefining architecture and construction, offering new opportunities and challenges. The emerging concept of industry 5.0 (16) means that humans and machines will be working together. 3D printing supports that with the promise of more efficient, sustainable and customized structures.

3.2. 3D Construction techniques

The evolution of construction has witnessed significant advances in recent decades. One of the most promising areas is the development of criteria for sustainable manufacturing. Tahmasebinia and its collaborators have investigated how criteria can be established for sustainable manufacturing in Construction 4.01. (17) This research suggests that combining modern techniques with sustainable principles can revolutionize the way structures are built.

Automation in construction has also been the subject of numerous studies, especially in the last decade. Vairagade (18) and his team have reviewed how the construction of structures can be automated, indicating that accuracy and efficiency can be significantly improved with the adoption of these techniques. In addition, workplace safety is a primary concern in construction. Disparate examples stand out, such as Gomes Soares Júnior and collaborators exploring how Industry 4.0 enabling technologies can be applied to improve workplace safety in construction (19), Yao's exploration (20) of the use of modern technology for building digital vehicle models, or Mahachi's work on innovative construction technologies to accelerate home delivery (21).

The transition to more advanced construction techniques has not only economic benefits, but also ecological ones. Shatov and his team have researched the ecological and economic benefits of transitioning to modern techniques on the path of Industry 4.0 (22). Finally, it's not limited to traditional materials. Verian and collaborators have researched the properties of new materials and the development of advanced delivery systems, suggesting that new materials and techniques can be developed to further improve efficiency and sustainability in construction (23).

4. METHODOLOGY

4.1. Introduction to the methodological approach

The methodological approach delineated in this section is designed to ensure that every phase of the design and construction process is meticulously addressed, from the nascent stages of conceptualization to the final documentation and presentation.

The methodology is structured to be both systematic and iterative, allowing for continuous refinement and optimization at each stage. This ensures that the designs not only meet aesthetic and functional requirements but are also optimized for the unique challenges and opportunities presented by 3D printing with concrete and clay.

For this research, we have chosen to employ Fusion 360 by Autodesk as the software that best meets our needs, with a multitude of academic references that validate their technical capabilities (24-26).

4.2. Workflow

The generative design workflow (27), especially in the context of 3D concrete and clay printing, represents a transformative approach in the architectural and construction domains. By harnessing computational algorithms and artificial intelligence, this workflow facilitates the exploration of a vast design space, producing innovative solutions tailored to the unique challenges and opportunities presented by 3D printing technologies. These solutions, grounded in predefined criteria and constraints, pave the way for architectural innovations that are not only aesthetically pleasing but also structurally stable and capable of being produced by the process defined in this flow.

Central to this workflow, shown in Figure 1, are three pivotal stages: Definition, Generation, and Integration. The Definition phase lays the groundwork, establishing the foundational parameters and objectives. This then seamlessly transitions into the Generation phase, where the computational power is harnessed to produce a myriad of design variations. Finally, the Integration phase ensures that these generated designs are harmonized with real-world applications, ensuring their viability and relevance. Together, these stages form a cohesive, iterative process that pushes the boundaries of what's possible in architectural de-sign and construction (28).

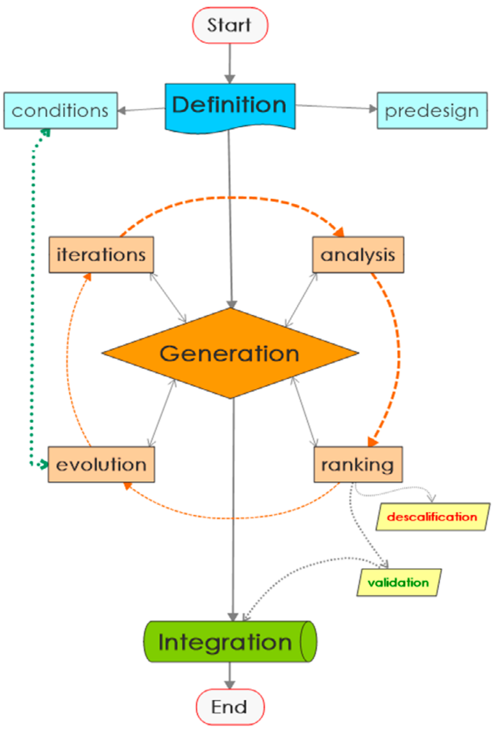

Figure 1. Generative Design workflow

Definition: The initial description is crucial to establishing the basis of the design. Here, architectural elements are identified and geometry issues such as shape, size, orientation, and spatial relationship between components are detailed. This stage is essential to ensure that the resulting design is coherent and functional. The relationship between the parts is especially important, as it determines how the different elements of the design interact and how they integrate into a cohesive whole (29).

The generative approach goes beyond simple form creation; it is a methodology that integrates functionality, aesthetics, and efficiency. For example, in a study on architectural design using generative algorithms and video projection mapping, we explored how algorithms can be used to produce façade design proposals, demonstrating the versatility and potential of these tools (30).

In addition, consideration of environmental factors and adaptation to local conditions are essential to ensure the sustainability and efficiency of the design (31).

Predesign: In this phase, the geometric foundations on which the final design will be built are established. These bases are divided into three main categories: Preserve Geometry, Obstacle Geometry and Starting Shape.

Preserve Geometry refers to the areas or elements of the design that must be kept in-tact during the generation process. These are essential aspects of the design that should not be altered. On the other hand, Obstacle Geometry indicates the areas or elements that should be avoided or that represent constraints in the design (see Figure 2 of column example). These obstacles can be structural, aesthetic, or functional. Finally, the Starting Shape is the initial shape or geometry from which the generative design process begins. This shape can be a simple basic geometry, or a more complex shape based on specific project requirements.

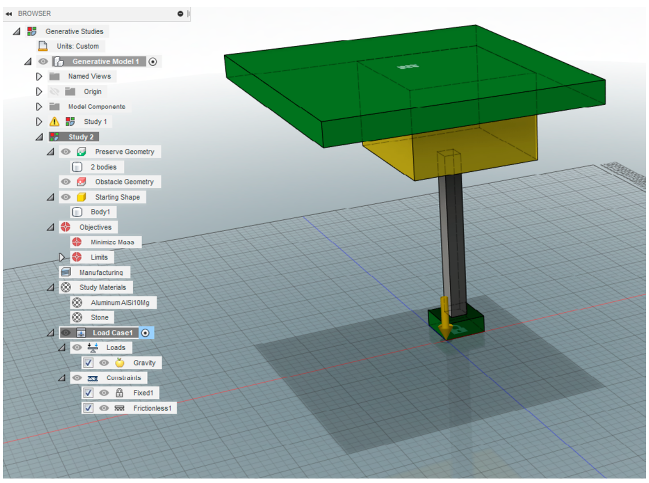

Figure 2. Column example: predesign conditions

Conditions: Structural restrictions refer to the constraints imposed on the connection or support points of a structure. These conditions determine how the load is transferred between parts of the structure and how the internal forces are distributed. There are three main types of structural conditions: Fixed, Pin and Frictionless. On the other hand, load types describe the different ways in which external forces act on a structure, determining how stresses and strains are distributed in the structure. The main types of cargo are Force, Pressure, Moment and Bearing Load.

Generation: is one of the most critical and complex components of generative design. At this stage the creation and exploration of multiple solutions based on the previously established definitions and conditions takes place. Through a computationally intensive process, shown in Figure 3, different design proposals are analyzed, evolved, iterated and classified to identify the most optimal solutions.

Analysis: Here, each solution generated is evaluated based on its performance, stability, and compliance with defined conditions and constraints. Factors such as load distribution, structural efficiency, and design aesthetics are considered. This analysis is essential to ensure that the solutions generated are not only viable but also functional and efficient.

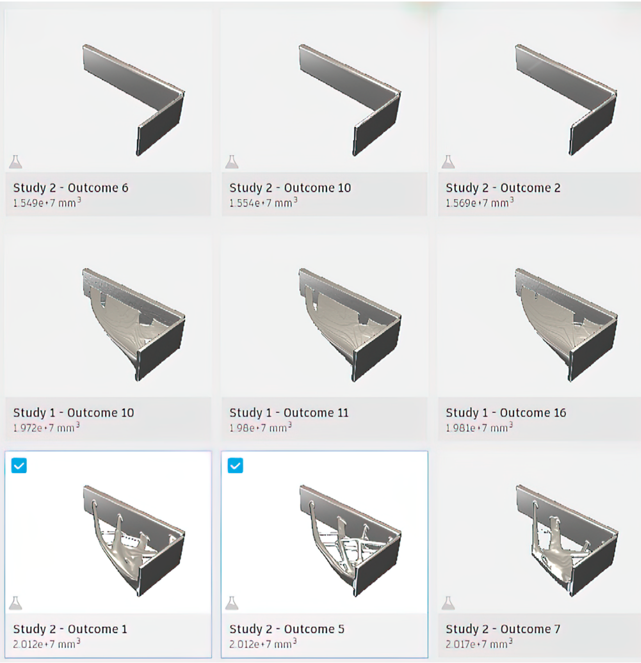

Figure 3. Stairs example: generative design solutions

Evolution: Based on the results of the analysis, solutions are modified and adapted to improve their performance. This process may involve altering parameters, adapting geometries, or incorporating new elements. Evolution is a dynamic process that seeks to continuously optimize the solutions generated. This part, along with the next, evolves and becomes more complex with each step as the divisions of the original form for study increase.

Iterations: Iterations are an essential part of the build phase. Since generative design is an exploratory process, multiple cycles of analysis and evolution will likely be required to arrive at optimal solutions. Each iteration refines and improves the proposals, bringing them closer and closer to the desired goal. Along with the previous step, it is a key part of being in which the multiple solutions to be evaluated are automatically generated. Each tool specified a maximum number of repetitions or a maximum level of detail or break-down to be reached to limit infinite repetition.

Ranking: Finally, the ranking ranks the solutions generated based on their performance and efficiency. The most promising solutions stand out, allowing designers and architects to focus on the proposals that deliver the best results.

Integration: The integration phase is the bridge between the generation of solutions and their final implementation in the design. Once multiple solutions have been generated and classified, it is essential to integrate them into the context of the overall project, ensuring that they align with the overall vision and objectives of the design. This phase is crucial to ensure that the generated solutions are not only optimal from a technical perspective, but also harmoniously integrated into the overall design.

Validation: Here, the selected solutions undergo a series of tests and evaluations to confirm their feasibility in the real context of the project. This can involve stress testing, aesthetic evaluations, or even simulations to predict how the solution will behave in different scenarios. Validation ensures that the generated solutions meet all requirements and expectations, and that they are ready to be implemented in the final design.

Disqualification: Although a solution may seem optimal on paper, there may be unforeseen factors or practical constraints that make it unfeasible in practice. Disqualification is the process of identifying and eliminating these solutions, ensuring that only the most robust and viable proposals advance to final implementation. The disqualification of solutions in generative design can arise for a variety of reasons, and it is essential to understand that not all of them are strictly related to functionality or technical feasibility. Economic factors, such as the cost of production or implementation, can make a solution, while innovative, not viable from a financial perspective. Technical aspects, such as weight, dimensions or compatibility with other design elements, can also be decisive.

End: The final phase marks the culmination of the generative design process and represents the point at which the selected and validated solutions are ready to be implemented in the final design. It is the moment when all the previous stages converge, and the solutions generated, analyzed, evolved, iterated, integrated, and validated are consolidated into a cohesive and optimized proposal. This phase not only involves the selection of the final solution(s), but also the preparation of all the documentation and details necessary for its implementation. This can include detailed drawings, technical specifications, bills of materials, and any other relevant information that facilitates the transition from generative design to actual construction or production.

4.3. Steps

This section refers to the specific actions that must be followed within the computer tool used for generative design, in this case, Fusion 360 or any other similar tool. These steps are essential to ensure that the generative design process is done in a systematic and structured manner, taking full advantage of the tool's capabilities and ensuring optimal results.

Preliminary Design and Conceptualization: After defining the conditions and pre-design in the workflow phase, the preliminary design and conceptualization act as the starting point for the generative design process. Here, the initial ideas are outlined and the basis for design development is laid. The structural conditions and load types identified above are considered to outline a conceptual design that meets the initial requirements.

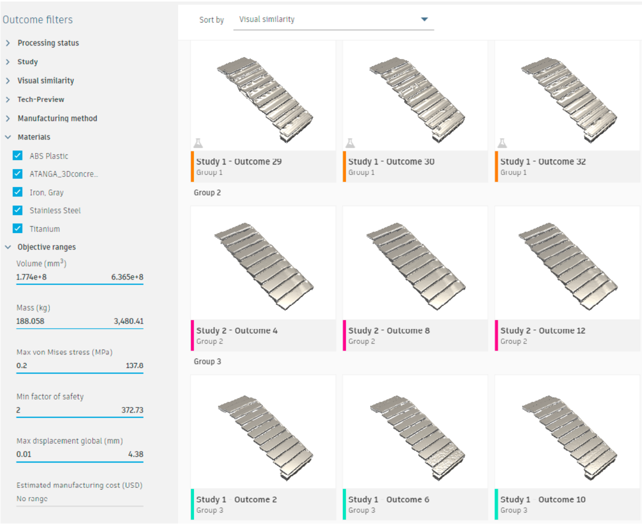

Figure 4. Prototyping by material: ABS, concrete, iron, steel and titanium in stair example

Parametric Design Development: Following the conceptualization, the parametric design is developed based on the initial model. Using parametric design tools, flexible models are created that can be adapted and evolved according to the needs of the project. This phase is closely related to the "Workflow" generation stage, where multiple design variations are explored.

Tools optimization and Material Considerations: With parametric design in place, it's essential to optimize tooling and consider the right materials for the project. Manufacturing characteristics and material characteristics, as shown in the Figures, play a crucial role in this phase. These considerations ensure that the design is not only aesthetically pleasing, but also functional and workable from a construction perspective. In figure 4, several materials solutions are shown.

It is at this stage that generative design differs significantly from topological optimization. While topological optimization focuses primarily on structural efficiency, eliminating unnecessary material to achieve an optimized shape, generative design goes further by considering aspects such as manufacturability, material selection, and other factors that can influence the feasibility and success of the final design (32).

Simulation and Analysis: Related to the analysis phase in the workflow, simulation and analysis are carried out to evaluate the performance of the design under different conditions. Advanced tools are used to simulate how the design will behave in the real world, ensuring that it meets all requirements and standards.

Prototyping and Iteration: Once the design has been analyzed, prototyping and iteration proceed. This phase aligns with the iteration stage of the workflow, where adjustments and modifications are made to the design based on the results of simulations and analyses.

Final Design Optimization: Before concluding the process, it is essential to optimize the final design. This phase is related to the integration stage of the workflow, where solutions are validated and disqualified. Here, final adjustments are made to ensure that the design is optimal in terms of functionality, aesthetics, and feasibility.

Documentation and Presentation: Finally, after the optimization of the design, we proceed to the documentation and presentation of the project. This phase is the finishing touch of the process, where all the details, drawings and specifications are prepared for the actual implementation of the de-sign. It relates directly to the "End" phase of the workflow, ensuring that the design is ready to be taken to the real world.

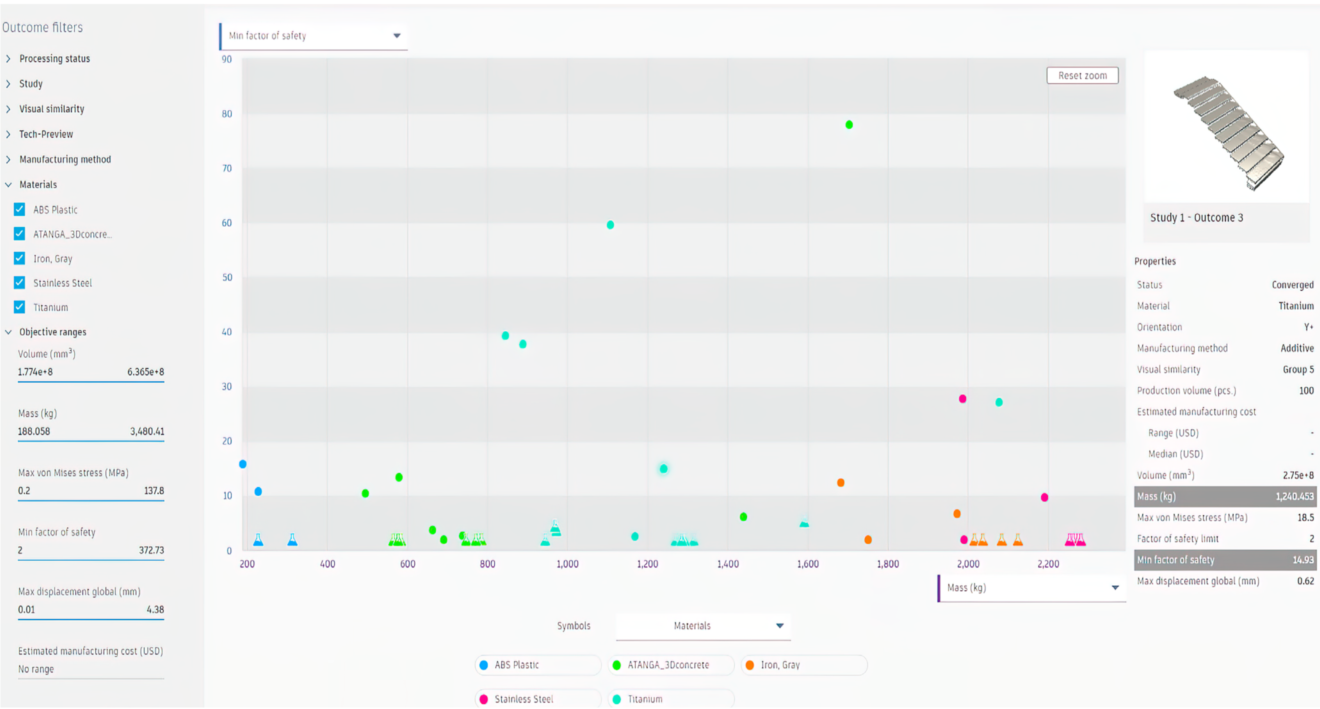

Figure 5. Analysis: Min Factor Safety vs Mass. ABS plastic, 3D Concrete, Iron, Stainless-Steel and Titanium comparison

5. 3D CONSTRUCTING APPLICATION

For this study, several construction elements of classic construction typology have been designed and analyzed, such as columns, slabs, bridges or walls, establishing relevant conclusions with these results.

Comparisons have also been made between various materials used for 3D printing, like concrete, clay, metal or plastic (see Figure 4), and different combinations of uses, loads and environmental conditions, according to regulations (see Figure 5).

The definitions of loads and relationships between the parts have been determined based on the traditional methodology of structural calculation, derived from the characteristics of the materials, manufacturing processes and use.

It is worth mentioning works such as those of Digital Grothesque I and II of Michael Hansmeyer and Eggshell pavilion by ETH Zurich and Gramazio Kohler as examples of direct application of designs based on generative processes through the use of large-scale 3D printing in architecture.

5.1. Evaluation of customization in 3D constructing

Customization in 3D construction is a concept that has gained relevance in the last decade, especially with the evolution of additive manufacturing technologies and the growing demand for unique architectural solutions. The ability to create custom structures that are tailored to the specific needs of users and the surrounding environment is one of the main advantages of 3D construction (33). From a mathematical perspective, customization in 3D construction is based on advanced algorithms that allow the optimization of structures based on specific criteria (34). These algorithms, which are derived from complex mathematical theories, allow for the creation of architectural forms that would be difficult, if not impossible, to achieve using traditional methods (35). Classical architecture was based on proportions and established rules that guaranteed the stability and aesthetics of structures (36). However, 3D construction makes it possible to break with these traditional norms and explore new forms and structures that better adapt to the environment and the needs of users (37).

From an engineering and construction perspective, customization in 3D construction offers significant advantages in terms of efficiency and sustainability (38). Custom structures can be designed to make the most of available resources, reducing material and energy waste (39). Energy saving is a crucial consideration in modern architecture, especially in the context of climate change and the growing demand for sustainable solutions (40). Custom 3D construction enables the creation of buildings that are not only aesthetically pleasing, but also energy-efficient (41). In addition, customization in 3D construction also has significant societal implications (42).

6. DISCUSSION

6.1. Development of Generative design algorithms for 3D constructing

The confluence of generative design and 3D construction represents a significant advance in the evolution of architecture and construction. This intersection evokes Oxman's contemporary reflections on the transition to a digital age in design, where computational tools and algorithms play a central role in the conceptualization and realization of structures (43). In this regard, the work of Dr Richard Buswell and Dr Peter Kinnell at Loughborough University. It is very relevant because it is one of the first initiatives that abandon the use of horizontal laminar fabrication in 3D printing, as was also did in the works of 3Dcons to the fabrication on vertical walls 3D printing with plaster.

Similar to Oxman's approach, generative design seeks optimal solutions within a set of parameters and constraints, harnessing the power of computation to explore a vast design space. On the other hand, 3D construction's ability to quickly materialize intricate designs reflects modern discussions about the integration of technology into architecture, as highlighted in Terzidis' works (44). Together, these technologies not only offer revolutionary aesthetic and functional possibilities, but also introduce unique challenges and considerations into the design and construction process. As we move into this digital age, it is essential that we draw on the research and reflections of contemporary leaders in the field to guide our practice and exploration.

The decision-making process in complex design scenarios, such as generative design, is intricate and often non-linear. An optimal decision at one stage may not align with the overall goal or subsequent phases. Advanced computational algorithms play a critical role by offering a holistic approach to decision-making, evaluating various outcomes and pathways, considering the entire process rather than isolated steps. This method ensures that decisions contribute to the best overall result, akin to urban planning or project management, where decisions support broader objectives. Additionally, with advancements in artificial intelligence, decision-making is increasingly sophisticated, with AI systems utilizing extensive data and complex algorithms to make comprehensive decisions that incorporate numerous variables beyond immediate visibility (45). As Biondi emphasized, the ethical design of AI-based systems for decision-making is crucial, ensuring that these systems are transparent, accountable, and devoid of biases (46).

6.2. Advantages and limitations of 3D constructing with generative design

The advantages of 3D constructing with generative design are manifold. This approach to architectural and construction design leverages computational algorithms to explore a vast design space, producing solutions that might not be immediately intuitive to human designers. The generative design process begins with the definition of design goals and constraints, which are then used to generate a multitude of design variations (see Figure 6). These variations are evaluated based on the set criteria, and the most suitable designs are further refined and optimized.

Figure 6. Column example: generative designs comparison

Generative design in architecture has long been studied, yet the traditional methods often required explicit rules and were heavily experienced-based (47). With the advent of modern computational tools and algorithms, the design solutions generated are not just based on empirical knowledge but can capture the implicit features and styles of a given context or dataset. For instance, using 3D building models from specific urban areas, neural networks can capture the implicit architectural features and styles, creating design solutions that are coherent with the existing urban fabric.

Despite these challenges, the integration of generative design in 3D construction offers a promising avenue for the future of architecture and construction. As computational tools become more advanced and the construction industry more adaptable, the synergy between generative design and 3D construction is poised to redefine the architectural landscapes of our cities.

Renowned mathematician Dr. Elena Petrova's work on "Optimization Techniques in Generative Architectural Design" (48) and her research highlights how advanced mathematical methods can be harnessed to achieve more efficient and innovative design outcomes.

6.3. Evolutionary impacts of 3D printing on traditional construction paradigms

The advent of 3D printing in the construction sector has ushered in a transformative era, challenging and reshaping traditional construction paradigms. Historically, construction methodologies have been linear and incremental, with designs often constrained by manual labor techniques, material limitations, and established architectural norms. However, 3D printing, with its ability to fabricate complex geometries and utilize diverse materials, has disrupted this status quo. One of the most profound impacts of 3D printing is its democratization of design and construction, with 3D printers becoming more accessible and affordable, a broader spectrum of designers, architects, and even laypersons can now engage in the construction process (49). This shift has led to a more inclusive design landscape, where innovative ideas can emerge from unexpected quarters.

3D printing has propelled construction towards sustainability by minimizing material waste through precise deposition (50), and innovations like drone-assisted printing further this efficiency. The technology also cuts labor costs and accelerates project timelines, enhancing economic feasibility. Nevertheless, integrating 3D printing demands a redefinition of architectural education and practice, challenging long-standing construction paradigms. Ultimately, while 3D printing fosters more inclusive, sustainable, and innovative practices, it requires a deep reassessment of traditional architectural norms.

6.4. Rewards of using specific materials for 3d printing in construction

Choosing the right material is crucial to the success of any construction project, and this is even more true in the context of 3D printing in construction. The adaptability of 3D printing allows for the utilization of a variety of materials, each with its own advantages and challenges (51). However, in recent years, there has been a growing interest in the use of sustainable and eco-friendly materials, such as clay, cements derived from accesible products, and wood (52).

Figure 7. Using 3Dclay part as recyclable mold for cement

Clay, in particular, has emerged as a preferred material in construction 3D printing due to its unique properties (53). It is an abundant and renewable natural resource that can be mined locally, thus reducing the carbon footprint associated with transporting materials. In addition, clay is biodegradable and non-toxic, making it a sustainable and environmentally friendly option (54). 3D printing with clay, known as "3D claying," allows for the creation of complex, custom structures with a natural, organic aesthetic that is difficult to achieve with other materials.

Cements derived from accesible products, such as lime-based cements and other accesible binders, offer similar advantages (51). These cements are less carbon-intensive than traditional cements and can "cure" or harden by absorbing carbon dioxide from the air, helping to reduce greenhouse gas emissions (55). In figure 7 it's an example of cement use with 3D printed clay mold.

Wood is also a renewable and biodegradable choice, sequesters CO_2, reducing the carbon footprint (56). 3D printing with wood allows the creation of lightweight and resistant structures with a warm and natural aesthetic. In addition, wood has natural insulating properties, which can improve the energy efficiency of buildings (57).

Choosing sustainable and eco-friendly materials for 3D printing in construction is not only beneficial for the environment but can also offer aesthetic and functional advantages (58). The adaptability of 3D printing allows architects and engineers to explore and experiment with these materials, taking construction and architectural de-sign to new frontiers (59).

7. IMPLICATIONS AND FUTURE DIRECTIONS

The advent of 3D printing in construction announces new potential in architecture for quick, efficient fabrication of complex, custom structures, promising transformative changes in building design and construction (60). Nevertheless, this calls for careful consideration of challenges to ensure sustainable integration into architectural practices (61).

3D constructing presents not only efficiency and customization benefits but also the opportunity for sustainable design through local and sustainable materials, enhanced by the technology's precision. This can yield more energy- and resource-efficient buildings, alongside human-centric designs tailored to user needs. Yet, challenges persist in assimilating this technology into practice, necessitating proper training for professionals and considering ethical and social implications, including equity in access. The continued evolution of 3D printing will be pivotal in architectural practice, requiring multidisciplinary collaboration to maximize its benefits and mitigate its challenges (62).

7.1. 3D Constructing integration in architectural practice

3D printing's incorporation into architectural practice is transforming design and construction approaches (63). This technology enables architects to create forms and structures once considered unattainable with conventional techniques. The rapid production of prototypes and full-scale models has significantly enhanced the design phase, facilitating quicker iterations and more precise visualization of design ideas. In addition, 3D printing is driving greater collaboration between architects, engineers, and builders. The digital and collaborative nature of technology facilitates communication and the exchange of ideas, resulting in more integrated and cohesive design solutions (64). Interdisciplinary collaboration is vital to overcome the technical and aesthetic challenges posed by 3D constructing (65). As technology continues to mature, it is essential for the architectural community to keep up with the latest developments and actively explore the possibilities offered by 3D printing. Only through experimentation and collaboration can the transformative potential of this technology be fully harnessed in architectural practice (66).

7.2. Potential for sustainable and customized design solutions

3D printing in construction has opened up a new horizon of possibilities in terms of sustainable and customized design solutions. The ability to fabricate project-specific architectural components allows for precise adaptation to local conditions, which can result in buildings that are more energy efficient and in tune with their surroundings (67). This customization can also reduce material waste, as exactly the quantities needed for each component can be produced, minimizing excess (68). From a sustainability perspective, 3D printing offers the opportunity to use recycled or locally sourced materials, thereby reducing the carbon footprint associated with the production and transportation of building materials (69). In addition, the ability to 3D print complex, optimized structures can result in buildings that require less material but maintain or even improve their strength and durability (70).

Instead, the customization enabled by 3D printing can lead to design solutions that respond specifically to the needs and desires of end users. This can translate into more functional and adapted spaces, which improve the quality of life of their occupants (71). As technology continues to advance, we are likely to see greater integration of 3D printing into the search for sustainable and customized design solutions in construction (72). However, it is essential that this adoption is done in a thoughtful manner, considering both the opportunities and challenges it presents (73).

8. CONCLUSIONS

The use of Generative Design (GD) in 3D constructing offers a number of significant advantages that are closely related. First of all, the GD enables precise optimization of the material and weight of structures. By using algorithms to generate efficient geometries, a substantial reduction in material consumption is achieved, which not only reduces costs, but also decreases construction waste, thus benefiting the environment. This material optimization translates directly into greater efficiency in construction. 3D printing allows the manufacture of building elements quickly and accurately, considerably reducing construction times compared to conventional methods. In addition, this technology can be applied in remote or hard-to-reach locations, making it easier to build in challenging environments.

Generative Design and 3D printing also complement each other in terms of design freedom and customization/adaptability. The GD provides greater design freedom by allowing architects and designers to create complex, custom shapes that would be difficult to achieve using traditional construction methods. This opens the door to the exploration of more aesthetic and functional designs. In turn, GD-based 3D printing allows for the customization of building components to suit specific project needs, which is particularly useful in the construction of homes and structures that must meet precise requirements or accommodate spatial constraints. This customizability and adaptability are intrinsically related to the design freedom provided by the GD, as both features allow designers to create structures that optimally meet the needs of a specific project.

The 3D constructing methodology, as an approach to construction with Generative Design techniques and three-dimensional printing, offers a superlative advantage by allowing the comprehensive inclusion of fundamental technical features (see Figure 8). These features include the precise definition of recyclable materials, the use of energy-efficient machinery, the almost total reduction of waste, and the possibility of combining elements from different categories into solutions of great geometric complexity during its manufacturing process.

Material optimization, one of the pillars of the GD, becomes an even more relevant aspect in the context of 3D construction. By using GD algorithms in 3D printing planning, a noticeable reduction in material consumption is achieved, which not only reduces costs, but also significantly decreases construction waste. This is especially valuable, as it contributes to environmental sustainability while saving on financial resources.

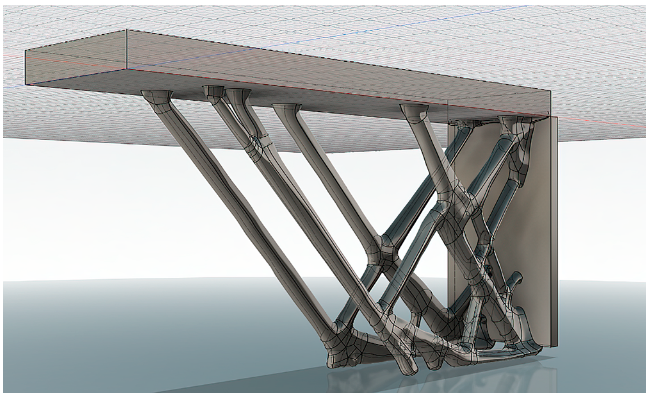

Figure 8. Generative Design final solution for 3D constructing

In addition, waste reduction is accentuated by combining 3D printing with the ability to use recyclable materials. The selection of materials that can be recycled or reused in the construction process promotes circularity and sustainability in the construction industry, further reducing its environmental impact.

The use of 3D constructing proves to be a highly beneficial solution in challenging scenarios, such as those following natural disasters or in isolated regions.

First of all, in situations following catastrophes, such as earthquakes or floods, 3D printing becomes an invaluable resource. The ability to build structures quickly and efficiently offers a more agile and effective response to provide shelter to affected communities. The GD makes it easy to adapt designs to changing conditions, accelerating reconstruction and recovery.

In addition, in isolated or hard-to-reach areas, 3D printing technology opens up new possibilities. It eliminates the need to transport heavy materials and equipment to remote locations, which can be logistically complicated and costly. Printing building components at the destination overcomes these limitations and enables construction in previously inaccessible areas, such as rural communities, or extreme environments, such as arctic or desert regions.

Third, customizability in complex environments is essential. GD combined with 3D printing makes it possible to adapt structures to the specific needs of a place. This adaptability is critical to addressing unique challenges and improving resilience in these complex environments.

In summary, 3D constructing represents an effective and versatile solution for construction in complex environments, due to its speed of response, the optimization of the construction process, the drastic reduction of waste, the adaptability to specific needs, the possibility of using recycled and recyclable materials, and the safety of workers combine to make this technology an invaluable tool in construction in general.

DECLARATION OF COMPETING INTEREST

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

AUTHORSHIP CONTRIBUTION STATEMENT

Javier Alonso Madrid: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing.

Guillermo Sotorrío Ortega: Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing.

Nils O.E. Olsson: Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing.

José Antonio Tenorio Ríos: Conceptualization, Investigation, Writing – review & editing.

REFERENCES

1. Alonso Madrid, J., Sotorrío Ortega, G., Gorostiza Carabaño, J., Olsson, N. E., Tenorio Ríos, J. A. (2023). 3D Claying: 3D Printing and Recycling Clay. *Crystals*, 13(3), 375. https://doi.org/10.3390/cryst13030375.
2. Sotorrío, G., Alonso, J., Olsson, N., & Tenorio, J. (2021). Printability of materials for extrusion 3D printing technologies: a review of material requirements and testing. *Materiales de Construcción*, 71(344), e267. https://doi.org/10.3989/mc.2021.11821.
3. Olsson, N. O. E., Arica, E., Woods, R., & Alonso Madrid, J. (2021). Industry 4.0 in a project context: Introducing 3D printing in construction projects. *Project Leadership and Society*, 2, 100033 https://doi.org/10.1016/j.plas.2021.100033.
4. Muñiz, M.M., Chantin, M., Vintila, C.R., Fabritius, M., Martin, C., Calvo, L., Poudelet, L., Canou, J., Uhart, M., Papacharalampopoulos, A. (2020). Concrete hybrid manufacturing: A machine architecture. *Procedia CIRP*, 97, 51-58. https://doi.org/10.1016/j.procir.2020.07.003.
5. Muñoz, I., Alonso-Madrid, J., Menéndez-Muñiz, M., Uhart, M., Canou, J., Martin, C., Fabritius, M., Calvo, L., Poudelet, L., Cardona, R., Lombois-Burger, H., Vlasopoulos, N., Bouyssou, C., Dirrenberger, J., Papacharalampopoulos, A., Stavropoulos, P. (2021). Life cycle assessment of integrated additive–subtractive concrete 3D printing. International *Journal of Advanced Manufacturing Technology*, 112, 2149-2159. https://doi.org/10.1007/s00170-020-06487-0.
6. Rahmat, N. F., Ali. N., Abdullah S. R., Abdul Hamid N. A., Salleh, N., Shahidan, S. (2023). Fresh properties and flexural strength of 3D printing sustainable concrete containing GGBS as partial cement replacement. S. *IOP Conference Series: Earth and Environmental Science,* 1205, 012042. https://doi.org/10.1088/1755-1315/1205/1/012042.
7. Robayo-Salazar, R., Martínez, F., Vargas, A., Mejía de Gutiérrez, R. (2023). 3D Printing of Hybrid Cements Based on High Contents of Powders from Concrete, Ceramic and Brick Waste Chemically Activated with Sodium Sulphate (Na2SO4). *Sustainability*, 15(13), 9900. https://doi.org/10.3390/su15139900.
8. Sotorrío Ortega, G., Alonso Madrid, J., Olsson, N.O.E., Tenorio Ríos, J.A. (2020). The application of 3D-printing techniques in the manufacturing of cement-based construction products and experiences based on the assessment of such products. *Buildings*, *10*, 144. https://doi.org/10.3390/buildings10090144.
9. Szabó, K. (2023). Component Development Using Topological Methods. *International Journal of Engineering and Management Sciences*, 8(2), 54-62. https://doi.org/10.21791/ijems.2023.2.6.
10. Kromer, R., Gruhier, E. (2023). Design teaching integrating additive manufacturing constraints. *Proceedings of the Design Society*, 3, 1327-1336. https://doi.org/10.1017/pds.2023.133.
11. Bañón, C., Raspall, F. (2021). 3D Printing architecture. Workflows, Applications, and Trends. *Springer Link*. https://doi.org/10.1007/978-981-15-8388-9.
12. San Fratello, V. (2021). 3D Printing Architecture. *TMS 2021 150th Annual Meeting & Exhibition Supplemental Proceedings. pp 37-49*. https://doi.org/10.1007/978-3-030-65261-6_4.
13. Alqenaee, A., Memari, A., Hojati, M. (2021). Transition from traditional cob construction to 3D printing of clay homes. *Journal of Green Building*, 16 (4): 3–28. https://doi.org/10.3992/jgb.16.4.3.
14. Chen, Y. (2021). Investigation of limestone-calcined clay-based cementitious materials for sustainable 3D concrete printing. Doctoral Thesis. Delft University of Technology. https://doi.org/10.4233/uuid:a0d9289b-9f24-4805-86ab-09f12714a946.
15. Darwish, L. R., El-Wakad, M., Farag, M. (2021). Towards sustainable industry 4.0: A green real-time IIoT multitask scheduling architecture for distributed 3D printing services. *Journal of Manufacturing Systems*, 61, 196-209 https://doi.org/10.1016/j.jmsy.2021.09.004.
16. Adel, A. (2022). Future of industry 5.0 in society: human-centric solutions, challenges and prospective research areas. *Journal of Cloud Computing*. 11, 40 https://doi.org/10.1186/s13677-022-00314-5.
17. Tahmasebinia, F., Sepasgozar, S., Shirowzhan, S., Niemela, M., Tripp, A., Nagabhyrava, S., Mansuri, Z., Alonso-Marroquin, F. (2020). Criteria development for sustainable construction manufacturing in Construction Industry 4.0. *Construction Innovation,* 20(3). https://doi.org/10.1108/ci-10-2019-0103.
18. Vairagade, S., Kumar, N., Singh, R., Tyagi, M. (2022). Automated construction of structures using 3D printing: A Review. Proceedings of the 12th Structural Engineering Convention, SEC 2022, 1(6). https://doi.org/10.38208/acp.v1.732.
19. Gomes Soares Júnior, G., Cardoso Satyro, W., Bonilla, S., Contador, J. C., Pires Barbosa, A., Monken, S. F., Martens, M., Fragomeni, M. A. (2021). Construction 4.0: Industry 4.0 enabling technologies applied to improve workplace safety in construction. *Research, Society and Development*, 10(12), e280101220280. https://doi.org/10.33448/rsd-v10i12.20280.
20. Cenglin Yao. (2021) Construction of digital model of auto parts based on 3D printing technology. *Journal of Physics: Conference Series*, 1744, 022016. https://doi.org/10.1088/1742-6596/1744/2/022016.
21. Mahachi, J. (2021). Innovative building technologies 4.0: Fast-tracking housing delivery through 3D printing. *South African Journal of Science*, 117, 11-12. https://doi.org/10.17159/sajs.2021/12344.
22. Shatov, S.V., Matsenko, O.M., Skrypka, Y.O., Danylenko, I. (2021). Ecological and economic benefits of the transition to 3d printing of buildings in the route of industry 4.0. *Ukrainian Journal of Civil Engineering and Architecture*. 1, 124-132. https://doi.org/10.30838/j.bpsacea.2312.230221.124.727.
23. Verian, K.P., Kowaleski, S.R., Carli, M.D., Bright, R., Maandi, E., Sill, G. (2020). Properties of 3D printing mortar with the development of a 3D Construction Printing (3DCP) delivery system. *Journal of the Transportation Research Board,* 2674(2). https://doi.org/10.1177/0361198120905595.
24. Baillon, P., Dixon, S., Faust, K., Herman, P., Seabring, H., Wood, S. (2022). Stereolithography 3D printed resin pressure enclosures applied in the marine environment. *OCEANS 2022, Hampton Roads, Hampton Roads, VA, USA*, 2022, 1-7. https://ieeexplore.ieee.org/document/9977042.
25. Orzeł, B., Stecuła, K. (2022). Comparison of 3D printout quality from FDM and MSLA technology in unit production. *Symmetry*, 14(5), 910. https://doi.org/10.3390/sym14050910.
26. Wojnarowska, W.M., Najowicz, J., Piecuch, T., Sochacki, M., Pijanka, D., Trybulec, J. and Miechowicz, S. (2021). Animal orthosis fabrication with additive manufacturing – a case study of custom orthosis for chicken. *Rapid Prototyping Journal*, 28(5), 824-832. https://doi.org/10.1108/RPJ-03-2021-0054.
27. Oxman, R. (2008). Digital architecture as a challenge for design pedagogy: theory, knowledge, models and medium. *Design Studies*, 29(2), 99-120. https://doi.org/10.1016/j.destud.2007.12.003.
28. Shea, K., Aish, R., Gourtovaia, M. (2005). Towards integrated performance-driven generative design tools. *Automation in Construction*, 14(2), 253-264. https://doi.org/10.1016/j.autcon.2004.07.002.
29. Buzzard, B., Demirkol, H., Inceoğlu, M. (2022). Architectural design with generative algorithm and video projection mapping. Eskişehir Technical University Journal of Science and Technology A - Applied Sciences and Engineering, 16th DDAS (MSTAS) Special Issue, 23. https://doi.org/10.18038/estubtda.1168718.
30. Grigorenko, A., Shopina. E. (2022). Generative design and adaptation for manufacturing of steering knuckle. Part II. *Bulletin of Belgorod State Technological University*, 8(2). https://doi.org/10.34031/2071-7318-2022-8-2-102-112.
31. Teixeira, G.S., de Campos, M.D. (2022). Influence of wind angle incidence and architectural elements on the external pressure coefficient of hyperbolic paraboloid roofs. *Design, Construction, Maintenance*, 2, 208-2016. https://doi.org/10.37394/232022.2022.2.27.
32. Belluomo, L., Trovato, M., Bici, M., Cicconi, P., Campana, F. (2023). An iterative generative design approach for multi-material components. CAD'23, Mexico City. https://doi.org/10.14733/cadconfp.2023.334-338.
33. Oxman, & Neri, & Rosenberg, & Louis, Jesse. (2007). Material-based Design Computation: An Inquiry into Digital Simulation of Physical Material Properties as Design Generators. International Journal of Architectural Computing, 5(1), 26-44. https://doi.org/10.1260/147807707780912985.
34. Mitchell, W. (1990). The logic of architecture: design. Computation, and Cognition. *Journal of Architectural Education,* 46(2), 104-106. https://doi.org/10.1080/10464883.1992.10734543.
35. Terzidis, K. (2006). *Algorithmic Architecture*. London: Architectural Press. https://doi.org/10.4324/9780080461298.
36. Ching, F.D.K. (2011). *A visual dictionary of architecture*. John Wiley & Sons. Retrieved form https://ia802804.us.archive.org/18/items/avisualdictionaryofarchitecture/A%20Visual%20Dictionary%20of%20Architecture.pdf.
37. Kolarevic, B. (2003). *architecture in the digital age: design and manufacturing*. London: Taylor & Francis. https://doi.org/10.4324/9780203634561.
38. Zhang, S., Teizer, J., Lee, J-k., Eastman, C., Venugopal, M. (2013). Building Information Modeling (BIM) and Safety:

Automatic Safety Checking of Construction Models and Schedules. Automation in Construction. 29, 183–195. https://doi.org/10.1016/j.autcon.2012.05.006.

39. Sass, L., Chen, L. (2016). Fresh Press Modeler: A generative system for physically based low fidelity prototyping. Computers & Graphics, 54, 157-165. https://doi.org/10.1016/j.cag.2015.07.003.
40. Beorkrem, C. (2012). Material strategies in digital fabrication. *Routledge*. Retrieved from https://www.routledge.com/Material-Strategies-in-Digital-Fabrication/Beorkrem/p/book/9781138654204.
41. Peters, B. (2013) Computation works: the building of algorithmic thought. *Architectural Design*, 83(2), 8-15. https://doi.org/10.1002/ad.1545.
42. Leach, N., Turnbull, D., Williams, C. (2004). Digital tectonics. Wiley. ISBN 978-0470857298.
43. Oxman, R. (2006). Theory and design in the first digital age. *Design Studies 27(3), 229-265.* https://doi.org/10.1016/j.destud.2005.11.002.
44. Terzidis, K. (2006). *Algorithmic architecture*. Architectural Press. Retrieved from https://www.routledge.com/Algorithmic-Architecture/Terzidis/p/book/9780750667258.
45. Alzyoud, A. (2023). Navigating the future: artificial intelligence's growing influence on decision making. *International Journal of Membrane Science and Technology*, 10(4), 2188-2194. https://doi.org/10.15379/ijmst.v10i4.2382.
46. Biondi, G., Cagnoni, S., Capobianco, R., Franzoni, V., Lisi, F., Milani, A., & Vallverdú, J. (2023). Editorial: Ethical design of artificial intelligence-based systems for decision making. *Frontiers in Artificial Intel*ligence, 6, 1250209. https://doi.org/10.3389/frai.2023.1250209.
47. Zhuang, X., Ju, Y., Yang, A., Caldas, L. (2023). Synthesis and generation for 3D architecture volume with generative modeling. *International Journal of Architectural Computing*, 21(2), 297-314. https://doi.org/10.1177/14780771231168233.
48. Petrova, E., Ivanov, A. (2020). Optimization of structural designs using evolutionary algorithms. Journal of Computational Design and Engineering, 7(2), 150-162. https://doi.org/10.1093/jcde/qwaa023..
49. Moyano-Sanz, S., Verdú-Vázquez, A., & Valiente-López, M. (2023). 3D Printing in architecture = Impresión 3D en arquitectura. *Advances in Building Education, 7*(2), 23-40. https://doi.org/10.20868/abe.2023.2.5112.
50. Yuan, P.F., Gao, T., Gu, S. et al. (2023). Methodology of fabricating 3D printing modified plastic single-layer panels with UAV positioning technology in the era of mass customization. *ARIN*, 2, 15. https://doi.org/10.1007/s44223-023-00037-w.
51. Bos, F., Wolfs, R., Ahmed, Z., Salet, T. (2016). Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. *Virtual and Physical Prototyping*, 11(3), 209-225. https://doi.org/10.1080/17452759.2016.1209867.
52. Eastman, C. (2011). Automated generation of layout models for early set-based design. *Automation in Construction*, 19(8), 977. https://doi.org/10.1016/j.autcon.2010.09.005
53. Lim, S. (2012). Developments in construction-scale additive manufacturing processes. *Automation in Construction*, 21, 262-268. https://doi.org/10.1016/j.autcon.2011.06.010.
54. Rael, R., San Fratello, V. (2018). Printing architecture: Innovative recipes for 3D printing. Princeton Architectural Press. ISBN 9781616896966..
55. DeJong, M. (2017). 3D printing of building components. *Journal of Architectural Engineering*.
56. Gosselin, C. (2016). Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders. *Materials & Design*, 96, 341-349. https://doi.org/10.1016/j.matdes.2016.02.039.
57. Khoshnevis, B. (2003). Automated construction by contour crafting—related robotics and information technologies. *Automation in Construction, 13(1), 5-19.* https://doi.org/10.1016/j.autcon.2003.08.012.
58. Le, T.T. (2012). Hardened properties of high-performance printing concrete. *Cement and Concrete Research*, 42(5), 665-672. https://doi.org/10.1016/j.cemconres.2012.02.003.
59. Wittel, F.K. (2020). Material-related aspects of extrusion-based 3D-printing of cementitious materials. *Cement and Concrete Research*, 133, 106084. https://doi.org/10.1016/j.cemconres.2020.106084.
60. Gershenfeld, N. (2012). How to make almost anything: the digital fabrication revolution. *Foreign Affairs*, 1(6), 43-57. https://www.jstor.org/stable/41720933..
61. Kostakis, V., Papachristou, M. (2014). Commons-based peer production and digital fabrication: The case of a RepRap-based, Lego-built 3D printing-milling machine. *Telematics and Informatics*, 31(3), 434-443. https://doi.org/10.1016/j.tele.2013.09.006.
62. Mellor, S., Hao, L., Zhang, D. (2014). Additive manufacturing: A framework for implementation. *International Journal of Production Economics*, 149, 194-201. https://doi.org/10.1016/j.ijpe.2013.07.008.
63. Lim, S., Buswell, R.A., Le, T.T., Austin, S.A., Gibb, A.G.F., Thorpe, T. (2012). Developments in construction-scale additive manufacturing processes. *Automation in Construction*, 21, 262-268. https://doi.org/10.1016/j.autcon.2011.06.010.
64. Khoshnevis, B., Hwang, D., Yao, K., Yeh, Z. (2006). Mega-scale fabrication by contour crafting. *International Journal of Industrial and Systems Engineering*, 1(3), 2006. https://doi.org/10.1504/IJISE.2006.009791.
65. Rael, R., San Fratello, V. (2017). Emerging objects: programming materiality. *Architectural Design*.
66. Zhang, J., Zhang, X., Gao, G., Dai, J. (2021). A review of the current progress and application of 3D concrete printing. *Automation in Construction*.
67. Tay, Y.W.D., Panda, B., Paul, S.C., Mohamed, N.A.N., Tan, M.J., Leong, K.F. (2017). 3D printing trends in building and construction industry: a review. *Virtual and Physical Prototyping*, 12(3), 261-276. https://doi.org/10.1080/17452759.2017.1326724.
68. Decker, M., Hahn, H., Strauss, A., Li, V.C. (2020). 3D printing of concrete: the impact of materials and printing process on mechanical properties. *Materials*.
69. Lowke, D., Dini, E., Perrot, A., Weger, D., Gehlen, C., Dillenburger, B. (2018). Particle-bed 3D printing in concrete construction – Possibilities and challenges. *Cement and Concrete Research*.
70. Ma, G., Wang, L., Ju, Y., De Schutter, G., Van Tittelboom, K. (2018). 3D printing using concrete extrusion: A roadmap for research. *Cement and Concrete Research*.
71. Wangler, T., Lloret, E., Reiter, L., Hack, N., Gramazio, F., Kohler, M., Bernhard, M., Dillenburger, B., Buchli, J., Roussel, N., Flatt, R.J. (2016) Digital Concrete: Opportunities and Challenges. RILEM Technical Letters.
72. Salet, T. A. M., Ahmed, Z. Y., Bos, F. P., & Laagland, H. L. M. (2018). Design of a 3D printed concrete bridge by testing. *Virtual and Physical Prototyping*, 13(3), 222-236. https://doi.org/10.1080/17452759.2018.1476064.
73. Salet, T.A.M., Ahmed, Z.Y., Bos, F.P., Laagland, H.L.M. (2018). Design of a 3D printed concrete bridge by testing. Virtual and Physical Prototyping, 13(3), 222–236. https://doi.org/10.1080/17452759.2018.1476064.