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**Review Article**

**Author(s):**
Leschok, Matthias; Cheibas, Ina; Piccioni, Valeria; Seshadri, Bharath; Schlüter, Arno; Gramazio, Fabio; Kohler, Matthias; Dillenburger, Benjamin

**Publication date:**
2023-08

**Permanent link:**
https://doi.org/10.3929/ethz-b-000611431



**Originally published in:**
Automation in Construction 152, https://doi.org/10.1016/j.autcon.2023.104918

Automation in Construction 152 (2023) 104918

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Review

# 3D printing facades: Design, fabrication, and assessment methods

Matthias Leschok [a,*,1], Ina Cheibas [b,1], Valeria Piccioni [c,1], Bharath Seshadri [c], Arno Schlüter [c], Fabio Gramazio [b], Matthias Kohler [b], Benjamin Dillenburger [a]

[a] Digital Building Technologies, ETH Zurich, Zurich, Switzerland
[b] Gramazio Kohler Research, ETH Zurich, Zurich, Switzerland
[c] Architecture Building Systems, ETH Zurich, Zurich, Switzerland

ARTICLE INFO

*Keywords:*
3D printing
Facade
Additive manufacturing
Computational design
Performance assessment
Building envelope

ABSTRACT

This paper presents a state of the art review for 3D printed facades. In the review, three main topics are identified: (i) computational design strategies for 3D printed facades, (ii) fabrication processes and materials, and (iii) performance assessment. The design section displays computational tools and methods for design to production of 3D printed facades. The chapter fabrication processes, materials, and applications illustrates the technology potential for facade application sorted by material groups. The performance assessment section presents current approaches to evaluating and validating the performance of 3DP facades. Finally, knowledge gaps, challenges, and future trends are discussed to offer insights into leading-edge solutions for facade design and fabrication.

## 1. Introduction

Facades are among the most complex elements in a building. Besides defining the architectural expression of a building, they represent the boundary between the external and internal environment, controlling the energy flow and matter from the outside to the indoor space. For this reason, they have a considerable impact on the user's comfort, indoor spaces' environmental conditions, and the buildings' energy performance [1]. Therefore, improvements in the performance of facades are essential to meet the goals of Net Zero Emissions by 2050 [2].

To reach high levels of efficiency and functionality, current facades are being reevaluated. The focus is to develop integrated building components tailored to the building's use, services, location, and orientation [3]. Conventional facades typically have standardized and homogeneous properties as they are assembled using multiple standardized, mass-produced components. This fact limits their ability to be tailored to their specific environmental conditions and their recyclability. A fundamental shift towards site-specific facades would offer novel opportunities for air tempering, improving indoor air quality, and electrical energy production [4]. Moreover, it holds great potential for reducing the energy demand, up to 30% (depending on specific climate and building type [5,6]) and improving indoor comfort. 3DP printing has the potential to propel this development as it allows for the creation of multifunctional, bespoke elements in a mono-material construction.

### 1.1. Site-specific facades

Site-specific facades are high-performance systems that can improve the overall building performance. These improvements can be achieved by site-specific construction or using active adaptive facade systems [7,8]. Compared to traditional systems, they require advanced control over their design, engineering, fabrication, and operations. Often, their multiple performances and operating mechanisms are facilitated by several functional layers [9], with increased complexity and sophistication of the facade systems [10]. Moreover, it poses a challenge to circularity and positive end-of-life of the components if multimaterial systems are connected/assembled in a non-reversible manner. For this reason, next-generation facades are required to integrate the multiple performative aspects with a clear design-to-disassembly strategy or create mono-material elements to reach a sustainable outcome.

### 1.2. 3D printed facades

The idea of adding multiple performances in a facade is far from new to architecture. Vernacular examples of traditional architectural types show a deep understanding of the role of facades as mediators between the interior and the exterior. More recently, in 1978, British Architect Mike Davies proposed the innovative concept of an integrated polyvalent wall, which has multiple performances in a single element [11].

* Corresponding author.
*E-mail address:* leschok@arch.ethz.ch (M. Leschok).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.autcon.2023.104918
Received 28 December 2022; Received in revised form 26 April 2023; Accepted 1 May 2023
Available online 9 May 2023

This facade draws inspiration from nature and process regulation in biological forms. For many years, however, technological gaps have prevented integrated climate-specific facades from being considered a viable alternative for the construction industry. This is because such facades were difficult to manufacture, maintain, repair, and recycle [12,13].

Only recently, advancements in material sciences, manufacturing, and computational methods opened up a new set of opportunities to build integrative climate-specific facades. Among these, 3D printing (3DP) is an emerging fabrication technique that enables the production of customizable components. The free-form design combined with the efficient and optimized placement of material through 3DP opens up the possibility for integrating multiple functionalities/performances in a single element [14,15]. Additionally, design freedom fosters the use of integrative design approaches with a closer interdependency between design, material, performance, and fabrication. Consequently, a customizable performative geometry can be 3DP from a mono-material, which is easier to disassemble and recycle at the end of its life cycle. Moreover, seamless design-to-fabrication workflows provide new opportunities for reducing development time and cost, and increasing performance and profitability [16]. Mass customization can be potentially achieved at no additional cost, contrary to most traditional manufacturing techniques, for which economic feasibility relies on large batch production [17].Therefore, 3DP offers the potential to materialize context-specific and high-performance facades with novel aesthetics [18].Material efficiency, low waste in additive manufacturing, and the availability of low-embodied-energy materials are promising solutions from a sustainability perspective [19]. Moreover, the performance integration into a monomaterial component can overcome the recycling challenges, common to conventional facades.

### 1.3. Scope and methodology

We define the scope of this review paper considering a broad meaning of the term facade. Facades are those vertical construction elements that form the division between inside and outside environments. This includes large-scale facade systems, such as concrete 3DP walls, single facade panels, like in polymer 3DP, up to small-scale elements, like bespoke metal connections and ceramic tiles, tackling either one or multiple functional requirements of building facades on different scales. After defining the scope, the review process consisted of four steps. The first step was a comprehensive literature search based on the combination of keywords referring to the facade domain, such as “facade”, “building envelope”, “cladding”, “wall” and “enclosure”, and to the 3DP domain, such as “3D printing”, “additive manufacturing” and “digital fabrication”. Scopus was used as the main search database. The second step entailed a check on the title and abstracts of the selected articles to exclude irrelevant material. The third step was an extensive analysis of the selected articles in order to develop a meaningful categorization system. As a result of this step, the literature was categorized into three main groups focusing on 1) the design of 3DP facades, 2) fabrication processes, materials, and applications 3) the performance assessment of 3DP facades. The fourth and last step consisted of an extension and refinement of the literature search based on the identified categories.

The corpus of reviewed studies covers approximately 180 items, the majority being peer-reviewed journal articles, book chapters, and a few conference contributions. Given the novelty of the research field, the review search was not limited to scientific articles but also included websites, web articles, and architecture magazines. The reviewed contributions belong to the domains of architecture, engineering, and material science, and the average year of publication is 2019 (see Fig. 1). Apart from a few old publications, the majority of articles date to the last four years, and the highest number of publications is from 2020, demonstrating growing research interest in 3DP of building facades.

To the present day, comprehensive summaries of 3DP for the construction sector exist [20–22]. However, these publications evolve mostly around the topic of fabricating free-form design, large-scale structural components, or in-depth technological details, without offering a comprehensive overview of 3DP facades. Only one facade-specific review paper exists [23]. None of these reviews, however, encompasses the entire process chain from design to production, to performance evaluation of 3DP facades, explores the relationship between these aspects and critically evaluates them. This review paper closes this gap by providing an extensive overview of the latest developments in the design, fabrication, and assessment methodologies of 3DP facades. We present the state-of-the-art and highlight the key challenges, research gaps, and future opportunities. Different 3DP methods are categorized by material group, with the aim of identifying the most relevant for the facade application.

The manuscript is structured as follows:

- Section 1 introduces the research motivation and relevance for the construction industry.
- Section 2 presents the most prominent design approaches for 3DP facades, by elaborating on the topic of computational design and performance integration.
- Section 3 focuses on material and fabrication processes. For each material group, the latest developments in regard to fabrication and performance integration are presented. Each subchapter is concluded with knowledge gaps, future opportunities, and research trajectories.
- Section 4 presents the performance assessment strategies for 3DP facades. Simulation and life cycle analysis are identified as essential elements when designing and building 3DP facades. Additionally,

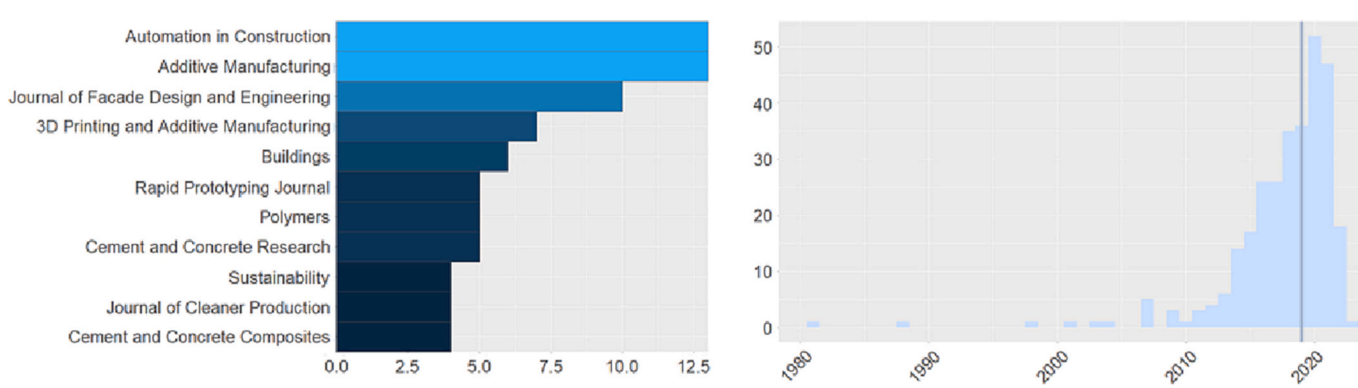



**Fig. 1.** Bibliometric analysis on reviewed literature. a) Most cited journals: the reviewed articles cover a variety of disciplines from construction, to manufacturing up to specific material system (concrete and polymers). b) Publication year: the majority of reviewed articles were published in the last four years and represent a growing research interest.

the challenges of performance validation for 3DP facades through experimental prototyping are listed.
- Section 5 concludes the presented sections highlighting challenges, limitations, and future opportunities.

## 2. Design for 3D printed facade

3DP or additive manufacturing (AM) offers novel opportunities in terms of geometrical freedom and complexity. Along with these opportunities, comes also the challenges of designing for 3DP processes. Traditional design tools and methods are not adequate for such complex production processes [16]. Therefore, novel design methodologies are required for 3DP facades. Such methodologies have to consider a seamless integration of 3D printing parameters and performative aspects of the facades in the design process. These performances can be structural, thermal, acoustic, and daylighting. Then, to fabricate these performance-informed designs, the computational tools have to incorporate the material and fabrication processes. Therefore, designing for additive manufacturing (DFAM) of 3DP facades is a novel methodology, which requires an integrative process between the computational design, material and fabrication, and environmental performance integration, see Fig. 2 [10].

### *2.1. Computational design*

The design of a 3DP facade is a complex task due to the multitude of fabrication and environmental parameters required to be integrated into the process. For this reason, computational tools are imperative for accommodating the increased complexity. Such tools should account for the relations between multiple design variables, such as environmental performances in an iterative generation of design alternatives [24]. Parametric design can offer iterative solutions by employing computational tools such as Grasshopper (GH) [25], and Dynamo [26], which are directly integrated into a 3D modeling software. Furthermore, parametric design is often coupled with performance optimization tools that facilitate the exploration of optimized 3DP facade designs. Moreover, with the increased computational experience of architects and engineers, engaging with Application Programming Interfaces (APIs) and Software Development Kits (SDKs) has brought new flexibility to modeling software.

One of the most unique features of AM is the possibility to design and fabricate infill. Parts can be designed as a combination of a solid outer shell and a porous internal articulation, as opposed to fully solid parts (Fig. 2.b.) [24]. Infill structures can be designed to decrease the weight of 3DP parts and improve their performance by enhancing the material's base properties [27]. For application in facades, these infills have the potential to be optimized and customized for specific boundary conditions and environmental performance requirements [28]. Some of the methods of modeling them are through cellular geometries or lattice structures [29]. These geometries are often defined by periodic repetition of unit cells or interconnected networks of struts, see Fig. 2 [30,31]. A major design challenge of these infill structures is their digital representation. Most commercial CAD software tools for AEC are based on boundary representation (BRep). BRep is defined by a solid shape, as a collection of connected surface elements [32].

While BRep representation is advantageous for subtractive manufactured objects, it comes short for 3DP applications, particularly, for cellular structures, due to their shape complexity [33]. This is because, BRep are defined as collections of surfaces that can end up with mismatches, discontinuities, self intersections, and non-orientable faces in complex designs [34]. Therefore, a solution for building complex cellular geometries is implicit or volumetric modeling (VM). In VM, geometries are built by function representation (FRep) instead of BReps. Geometric operations and transformations are defined mathematically, and objects are only generated in the final step, for rendering or export [35]. This approach results in a faster computational process and minimal requirement for post-processing. Commercial software packages such as Ntopology [36] or spherene [37] have been developed to specifically aid the design of 3DP cellular and lattice structures. Additionally, open-source plug-ins such as Axolotl [38] are integrated in the Grasshopper parametric modeling environment, which makes the process available to a wider public.

### *2.2. Performance integration*

Integrating performance indicators in the computational design is essential to building a site-specific, sustainable, and cost-efficient 3DP facade. These performance indicators can be integrated with optimization tools that incorporate environmental parameters, such as daylight, as well as structural strength, thermal, and acoustic parameters. To integrate environmental performance aspects in the design process, several climate-specific factors have to be considered. For example, Craveiro et al. [28] displayed how 3DP fabrication parameters of concrete walls can include a material design module with different types of cork-concrete aggregates. The aggregate has thermo-mechanical performance assigned to discrete parts of the geometry. Additionally, to

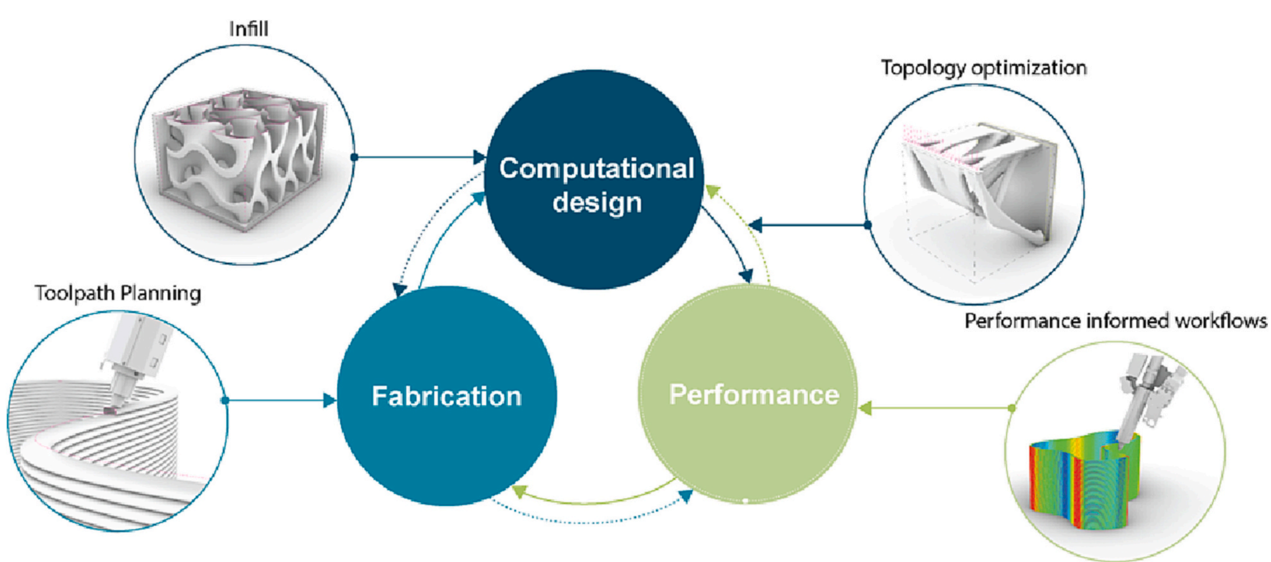



**Fig. 2.** DFAM methodologies for 3D printed facades. Topology Optimization, Infill Design, Toolpath Planning, and Performance informed workflows.

thermal performance, cost and fabrication efficiency can also be included as performance indicators in the design process [39]. Mostafavi et al. [40] presented a design workflow for optimized material distribution in a robotic fabrication process. Similarly, Naboni et al. [41] developed an algorithmic design workflow for material and structural topological optimization on multiple interdependent scales in the Trabeculae Pavilion.

To optimize the 3DP facade design, material efficiency is a fundamental feature in the fabrication process. Together with the use of low-embodied energy materials, the optimization of material distribution is a major design direction in the challenge of the building sector decarbonization. Topology optimization (TO) is an optimization method that combines a numerical solution method, such as Finite Element Analysis (FEA), with an optimization algorithm that iteratively improves the material distribution within the design space, given a set of boundary conditions and loads [42] (Fig. 2). Several studies demonstrated the synergies between TO and material design as 3DP allows the fabrication of components with intermediate densities and material properties [43,44]. Application of TO to the design of facade components can be found in metal 3D printed connections with optimized material use and wall components where structural optimization results in voids and cavities. Those can integrate additional environmental performances such as thermal insulation, soundproofing, and embedded utilities [45,46]. Moreover, TO principles applied to toolpath planning were explored for robotic additive manufacturing of clay walls [39].

Nevertheless, there is a lack of complete software packages that combine DFAM features with TO methodologies [43]. Manufacturing constraints and parameters such as dimensional accuracy, printable overhang, need for support material, and printing time are often accounted for at a later stage of the design as a rationalization process of the initial optimized design [47]. Such solutions are often application-specific and lack generalizability. A few commercial software options, such as Optistruct [48] incorporate 3DP constraints, lattice designs, and TO procedures. However, the geometry complexity of these parts is often such that an intermediate step of simplification and smoothening is needed before the geometry can be transformed into a mesh for fabrication, as in [31,49]. Another challenge of TO is the material properties description and validation of the entire topologically optimized part and the 3D printed material. Additional efforts towards the establishment of standard testing protocols and material property databases are needed, along with real-time monitoring of the production processes to correlate printing factors and part properties [20]. These aspects are especially crucial for facade application as behaviors observed on a smaller scale need to be validated for large-scale components. Yet, the advantage of TO is that it could potentially scale up from the design of structural nodes to that of entire facade panels. Paoletti et al. [50] describes the possibility of generative TO for the optimal material organization according to wind load compliance and stiffness. Moreover, since building facades are inherently multi-functional components, the multi-objective TO, combining structure with thermal control and daylighting, represents a promising design approach. Finally, for application in facades, TO should embed additional safety levels or redundancies to make the optimized design robust to disturbance events such as unanticipated or exceptional loading cases and human factors [51].

TO can work synergistically with infill design to materialize variable-density components. A common approach is to design infill structures with a chosen base shape to periodically fill the component's volume following a density map derived by TO [52]. For example, Naboni and Kunic [30] propose a computational approach to design nature-inspired cellular structures for materially efficient facade components. They also show how to use TO and porous structures to design structurally efficient objects that meet the 3DP constraints. The Spider Bracket features a topologically optimized overall shape consisting of solid parts and variable density lattice structures for reduced compliance and improved thermal behavior [31].

Along with performance indicators, economy, printing time, and process efficiency are also relevant criteria for displaying the full potential of 3DP facades [30,40]. Sustainability aspects, such as the components' life-cycle energy and carbon intensity, should also be considered in DFAM.

### 2.3. Fabrication informed design

Material and fabrication methods are essential parameters for fabricating a 3DP facade from a virtual design into a physical prototype. The process by which material behavior, fabrication parameters, and geometry are integrated into the computational design method is known as toolpath planning, or slicing (see Fig. 2). Slicing is the process of contouring a 3D model of the final object (e.g., STL file format) into its individual layers [22]. From this layer-based information, the final tool path, such as a G-Code, is created. Mature 3DP processes create fabrication data and toolpaths using proprietary slicing software. Some slicing software supports a novel data format, called Additive Manufacturing File (AMF). AMF contains additional information compared to a standard-triangulation file format. Print paths are often created based on customized computational tools for novel processes, such as concrete 3DP or large-scale polymer extrusion. The toolpath can be defined with a Robot Code, such as RapidCode or KRL, that contains the print path, tool orientation, speed, and acceleration.

For facade elements, toolpath planning plays a key role in environmental performance. This is because performance is highly dependent on the layer-to-layer bonding, irrespective of the 3DP method, [9,53]. Ashrafi et al. [54] investigated the effect of layer properties, number of contours, and printing time on the deformation of large 3D-printed concrete elements. By testing different samples, material behavior, such as geometry deformation and accuracy, was strongly correlated to the toolpath design. Although slicing plug-ins such as Silkworm [55] exist, in most applications, custom-made scripts are created to tune printing parameters and robotic motion. Kontovourkis et al. [39] developed a parametric-integrated algorithm to generate contour polylines by slicing any geometry and offsetting them according to the printing parameters (layer height and width). Their algorithm generates different infill geometries, based on the required density, and sorts the resulting polylines to minimize the robotic movement during printing and non-printing motions. Molloy and Miller [56] explored the potential of freeform 3DP through direct toolpath planning and not relying on layer-based slicing software. Their direct toolpath planning allowed them to print spatially, overcoming the traditional 2.5D printing approach. While planar slicing is a robust and simple technique, more advanced slicing methodologies Mitropoulou such as multi-axis, multi-directional, and adaptive slicing are being investigated to mitigate the stair-step effect and minimize the need for support structures [9,57].

To summarize, the method of designing and building a 3DP facade has to consider an interlinked process of computational design, performance integration, and fabrication constraints. However, such methodologies need a large number of iterations and evaluations in the design process to identify optimized solutions. Complete software packages, such as Ansys and 3D Experience, provide tools for geometry preparation, TO procedures, FEA, validation, and printing process simulation. However, these packages are not yet designed for largescale applications; therefore, custom software needs to be further developed for the application of 3DP facades. Such workflows are usually project-specific, and the AEC sector would benefit from the establishment of informed design approaches with general applicability. Essential in this approach is also to provide open access to tools and design methodologies to propel knowledge and methods transfer between different disciplines within and outside the AEC sector [15,58]. Finally, a database of fabrication processes and material properties would allow a comprehensive overview of the 3DP facade design potential.

## 3. Fabrication processes, materials, and applications

The following chapter presents a state-of-the-art of 3DP technologies for facade application, sorted by material groups. This section displays studies and projects which aim to manufacture performative facade components with varying degrees of complexity. The focus of this section is to identify the implications of fabrication technology and material on the design and manufacturing of 3DP facades. We discuss the benefits and challenges connected to each technique and highlight their potential for creating performative facade components.

### 3.1. Thermoplastics

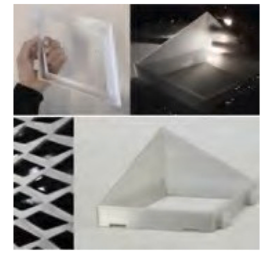
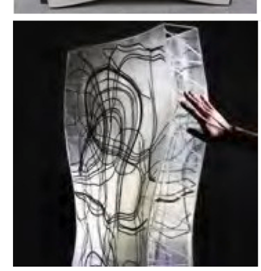
Polymers can be 3D printed with a wide variety of processes, such as material extrusion, Stereolithography, Multi Jet Fusion, PolyJet, Selective Laser Sintering, and Digital Light Processing. These processes use different polymer base materials to create 3D geometry, ranging from small to large-scale applications. This paragraph focuses on material extrusion processes that use thermoplastic polymers to create three-dimensional objects. The major benefit of this technology is that it is the only 3DP technology that can create translucent, nearly transparent components at a large scale. For a more detailed review of other AM methods of polymers, please refer to [59]. Thermoplastic extrusion uses filaments or granular polymer materials as feedstock for 3D printing. The largest thermoplastic extrusion setup can be currently found at Thermwood (30 × 6.7 × 3 m) [60]. Those systems are relevant for architecture, because of their fabrication size, material output (up to 68.0 kg/h), and competitive pricing. Furthermore, an increasing number of pellet extruder providers, such as CEAD, MassivDimension, and Pulsar, offer easier access at a competitive cost to large-scale thermoplastic 3D printing.

One of the main challenges of thermoplastic 3DP is the anisotropic mechanical behavior [53,74]. The printing direction has a large impact on the structural properties and, therefore, its final use case. To overcome weak layer bonding, the project Cloud Effects from Studio Roland Snooks [69] integrates channels in the 3DP elements that are infused with continuous carbon fiber, after assembly into a larger structure. Other projects rely on a substructure to take all critical loads or are not intended for outdoor applications. Posttensioning of elements as shown by Biswas et al. [72] as a viable method of reinforcing the final geometry. A more speculative approach has been investigated by Kwon et al. by addon-3D printing continuous carbon fiber strands onto thermoplastic 3DP components [66].

Researchers have been increasingly investigating thermoplastic 3DP for functional facade applications in the past decade. Researchers from TU Delft developed a digital workflow in the Rhinoceros-Grasshopper environment to design 3DP thermoplastic facades with internal cellular structures to optimize thermal insulation [67]. Results were generated using FEA simulations and calibrated by empirical data from standardized heat flow meter tests. It was shown that a mono-material 3D printed facade can be created with a 29 cm thick panel complying with the thermal insulation requirements of the Dutch building code. ETH Zurich researchers showed how a computational design tool can be used to manipulate the infill structure of 3DP facades [68]. Furthermore, they provided initial investigations on how a 3DP facade can be discretized and assembled using 3DP connection details. Sarakinioti et al. investigated closed cellular structures for thermal insulation in a thermoplastic 3DP facade using an experimental 'hot-box' set-up [63]. The authors showed that by using a low conductivity (PETG) material and specific cellular structures, high-performance thermal insulation could be achieved.

Researchers focus also on using translucent/transparent thermoplastic materials for creating functional prototypes at an architectural relevant scale, see Table 1. A study at TU Delft investigated a multi-functional 3DP facade to account for annual seasonal variations in temperature [63]. The concept uses air cavities and a water-based

**Table 1**
Thermoplastic 3DP for facade application.

| Description | Image |
|---|---|
| **Research Projects**<br>**3DP shading devices. 2016**<br>*Additive Manufacturing for daylight. Towards a customized shading device* [61]. Delft University of Technology. Digital framework for the design of 3d printed daylighting and shading devices. |  |
| **Fluid Morphology. 2017.**<br>*Fluid Morphology – 3D-printed functional integrated façade* [62]. Technical University of Munich (TUM). Research on monomaterial functional integrated facade with a large-scale outdoor prototype. |  |
| **Sponge 3D. 2017.**<br>*Developing an integrated 3Dprinted facade with complex geometries for active temperature control* [63]. Delft University of Technology. Investigations on closed cellular structures for thermal insulation in a thermoplastic 3D printed facade. |  |
| **Double Face 2.0. 2018.**<br>*Double Face 2.0 A lightweight translucent adaptable Trombe wall* [64]. Delft University of Technology. 3D printed Trombe wall for passively reducing the energy demands of buildings. Combining polymer 3D printing with phase changing materials (PCM). |  |
| **Artificial aging tests of 3DP shading elements. 2019.**<br>*Fabrication and durability testing of a 3D printed facade for desert climates* [65]. Politecnico di Milano. Artificial aging tests of thermoplastic 3D printed shading elements. Testing different materials and objects of different size. |  |
| **Digital Composites. 2019.**<br>*Digital Composites:Robotic 3D Printing of Continuous Carbon Fiber-Reinforced Plastics for Functionally-Graded Building Components* [66]. ETH Zurich. Addon 3D printing of continuous carbon fibers on polymer 3D printed elements. |  |

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working fluid to insulate and regulate heat flows through the facade. Tenpierik et al. investigate the possibility of combining phase-changing materials (PCM) with thermoplastic 3DP elements to create a Trombe wall [64]. They used computational fluid dynamics (CFD) models to simulate phase change materials encapsulated in 3d printed

**Table 1** (*continued*)

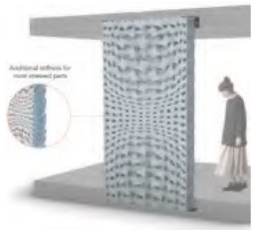
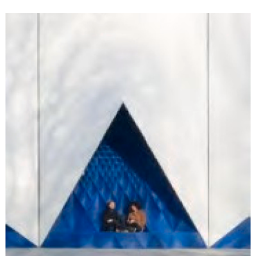
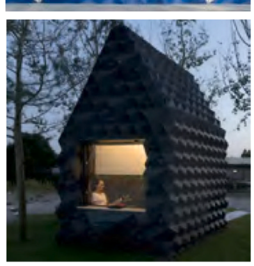
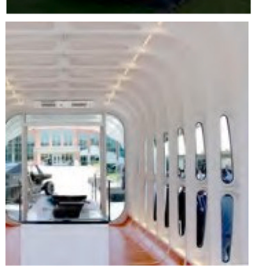
| Description | Image |
|---|---|
| **Infill design for insulating facade. 2020.**<br>*Performance-Driven Approach for the design of cellular geometries with low thermal conductivity for application in 3D-printed facade components* [67]. Delft University of Technology. Development of a digital workflow to design to optimize thermal insulation of 3DP facades. |  |
| **Facade prototype. 2020.**<br>*Large-scale 3D Printing for Functionally-Graded Façade* [68]. ETH Zurich. Research on connections, infill design and prototyping using different large-scale 3D printing setups. |  |
| **Super Composite. 2021.**<br>*Super Composite: Carbon Fiber Infused 3D Printed Tectonics* [69]. Royal Melbourne Institute of Technology. Centre for Innovative Structures and Materials, RMIT University. Carbon reinforced components to overcome weak layerbonding. |  |
| **Applied Research Projects** | |
| **Europe Building. 2015.**<br>*Europe Building*, 300 m2 3DP facade for mobile event/conference space [70]. DUS Architects, Netherlands. |  |
| **Urban Cabin. 2015.**<br>*Urban Cabin.* Polymer 3D printed facade in combination with cast concrete [71]. DUS Architects, Netherlands. |  |
| **AMIE. 2016.**<br>*Additive Manufacturing Integrated Energy—Enabling Innovative Solutions for Buildings of the Future* [72]. Oak Ridge National Laboratory, The University of Tennessee, Skidmore, Owings & Merrill LLP. Development and fabrication of a compact housing using large-scale polymer extrusion. |  |

**Table 1** (*continued*)

| Description | Image |
|---|---|
| **Sensilab Studio. 2020.**<br>*Printed Assemblages, a Co- Evolution of Composite Tectonics and Additive Manufacturing Techniques* [73]. RMIT University, Studio Roland Snooks. Large-scale polymer 3D printing for indoor application. |  |

thermoplastic facades for thermal control. However, the challenge of using phase changing materials in combination with currently available 3DP thermoplastics is twofold: a) the 3DP parts might not always be watertight and therefore the liquid PCM can escape the object, and b) the heat released from the PCMs might deform the thermoplastic shell due to the material's low glass-transition temperature. The authors concluded that creating smaller, stacked, PCM modules ensured less convective heat transfer in the vertical direction.

A multi-performative approach was investigated by Mungenast on 3D printed, mono-material (PETG), and multifunctional facade prototypes [62]. Mungenast concluded the following: (i) layer alignment and inner 'infill' structures heavily influence structural failure; (ii) self-shading geometries and internal cellular structures should be simulated and designed to avoid facade overheating, to optimize daylight transmission, and thermal insulation; (iii) UV testing resulted in discoloration; (iv) lack of water tightness and presence of dust during the printing process led to condensation and algae formation. Grassi et al. prototyped a facade shading system for hot-dry climate conditions using high-temperature resistant thermoplastic (Polylactic acid, PLA) with additives [65]. They performed accelerated aging for durability testing (Temperature, UV resistance) using the Reference Service Life method and concluded that pure PLA shows better durability than fiber-reinforced (delamination) and metal-colored PLA. Karagianni et al. developed a performance-informed digital framework for the design of 3DP daylighting and shading devices. These are fabricated using small-scale thermoplastic 3D printers and snap-fit connection allows for an easy assembly [61]. With "SensiLab Studio"(2017) and the project at "RMIT school of design" (2020) [73] Studio Roland Snooks showcased large-scale thermoplastic 3DP for indoor applications, passing indoor fire and building regulations in Australia. DUS architects created the facade for a temporary pavilion for the European Union using bioplastics [70]. The printed elements were partly used as a lost formwork for concrete. A similar approach was taken for the Urban Cabin, a 25 cubic meter large cabin that was entirely 3D printed out of biodegradable thermoplastics [71]. In a collaborative research project, the Oak Ridge National Laboratory (ORNL) has created the AMIE, the Additively Manufactured Integrated Energy project [72]. The facade prototype (10.9 m × 3.6 m × 4.2 m) is constructed from multiple thermoplastic 3DP structural elements, which are insulated using low-cost vacuum insulation pads. In another project, the ORNL used thermoplastic 3DP formwork for casting bespoke concrete facade panels [75].

Thermoplastic 3DP has been successfully scaled up to facade application. Furthermore, they allow for mono-material facade solutions which can have a positive impact on their sustainability. Although thermoplastics has been recently used for real-scale projects, further research needs to tackle topics such as thermal insulation, the reaction to fire and fire propagation, UV resistance, optical properties, and connection details. Additionally, thermoplastic 3DP facades' transmissive properties and their potential solar gains require further investigation. The argument for mono-material, multifunctional 3DP polymer facades need to be further strengthened by investigations on sustainability aspects. It has been shown that, depending on the method of recycling, thermoplastics can be recycled up to 5 times without severely affecting the thermomechanical properties [76]. Other studies show that recycling always goes in hand with the degradation of material characteristics [77,78]. However, these studies directly recycle the specimens after testing them and do not consider the lifecycle of a facade, or the aging behavior due to UV radiation. Only by understanding the material lifecycle and the facades' environmental and performative aspects, can holistic design approaches towards mono-material 3DP thermoplastic facades be formulated.

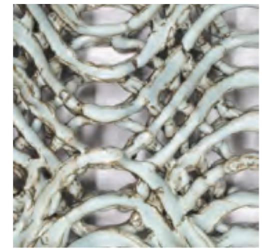
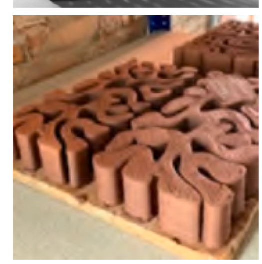
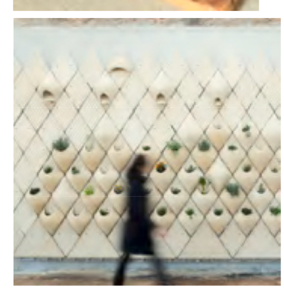
### 3.2. Clay-based materials

3DP of clay-based materials contains a wide variety of approaches to building environmentally friendly facades. Clay-based materials refer to clay, adobe, cob, and rammed clay [79]. These materials are generally composed of clay, gravel, sand, silt, and water, with sometimes additional fibers and stabilizers. The fabrication technique of these materials is dependent on the material type, and post-processing demands [80]. Adobe and green body clays can use material extrusion, compaction, and molding [81]. Ceramics can be manufactured in a two-step process: initially, a clay green body is digitally fabricated and then is fired in a second step for hardening. Because ceramics require a sintering process, they can be manufactured with binder jetting, digital light processing, powder bed fusion, material extrusion, and sheet lamination. In facade applications, 3DP of clay-based materials is advantageous because local materials can be used. These can vary from small-scale elements such as tiles [82] or bricks [83] to large- scale exterior walls [84]. Research on clay-based 3DP facades focuses on using local clay materials to explore novel methods for ecological wall construction, see Table 2. Facade elements have been investigated for several performances, such as thermal insulation, vapor permeability, mechanical strength, and construction efficiency. For example, Dubor et al. and Wasp identified how such walls can be optimized for thermal, ventilation, daylight, or structural performances [85]. Gomaa et al. concluded that the integration of air cavities and soil-straw elements in the fabrication process improved the thermal insulation of brick elements [86]. These researchers concluded that the printing time of bespoke wall elements with complex shapes was similar to conventional ones.

The reasons for using adobe or clay for 3DP facade walls is because of their beneficial mechanical strength, low material costs, and low environmental impact [81]. Additionally, raw clay can be easily recyclable if they do not contain limestone and cement. Nevertheless, 3DP of adobe and clay is relevant for climates with lower relative humidity changes. This is because certain 3DP claybased materials require additional stabilizers or protection to prevent material degradation from precipitation, mold, and high-temperature fluctuations in specific environments. A way to mitigate these challenges is by using ceramics as a 3DP material [87]. Ceramics, compared to clay, have appealing physical and mechanical properties, such as high-temperature strength, corrosion resistance, water tightness, high hardness, superior mechanical properties, and electrical and thermal conductivities [88]. For this reason, 3DP ceramics have been implemented for facade application in the form of modular components, such as bricks, tiles, or cladding [89–91]. Nevertheless, the disadvantages of these materials are that they require additional fabrication energy due to the sintering step, and they cannot be recycled and reused. Therefore, ceramics are not considered a viable solution from a sustainability perspective. An essential part of the 3DP process of clay-based materials is the computational framework. Recent research in computational design has focused on non-conventional form-finding [39]. AlOthman et al. displayed how to 3DP spatial toolpaths compared to layered deposition techniques to optimize fabrication time potentially and material use [92]. At the same time, Friedman et al. and Rosenwasser et al. incorporated weaving techniques in the 3DP process. They proved the 3DP clay potential on non-flat surfaces to reduce fabrication time [93,94].

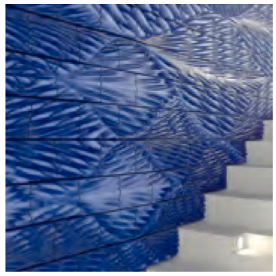
Nevertheless, 3DP of clay-based materials is confronted with several

**Table 2**
Clay-based 3DP for facade application.

| Description | Image |
|---|---|
| **Research Projects** | |
| **Clay Non-Wovens. 2017.**<br>*Clay Non-Wovens* [94]. Cornell University, Sabin Design Lab. Woven system of porous cladding panels for natural daylighting performances. |  |
| **3DP earth architecture. 2017.**<br>*Energy Efficient Design for 3D Printed Earth Architecture* [85]. Institute for Advanced Architecture of Catalonia. Analysis of 3D printed mud performance and simulation for the optimization of a wall prototype. |  |
| **Spatial Print Trajectory. 2018.**<br>*Spatial Print Trajectory: Controlling Material Behavior with Print Speed, Feed Rate, and Complex Print Path* [92]. Harvard University. Controlling clay material behavior with 3D print speed, extrusion rate, and complex print path. |  |
| **Biodigital Clay Bricks. 2021.**<br>*3D-Printed Biodigital Clay Bricks* [83]. Universitat Internacional de Catalunya, Helwan University. 3D printed clay bricks. |  |
| **CO-MIDA. 2022.**<br>*CO-MIDA: Biophotovoltaic Vertical Gardens 3D Printed With Clay* [91]. Institute for Advanced Architecture of Catalonia. Ceramic modular tiles made of 3D printed clay, for growing edible plants in built environments. |  |
| **Applied Research Projects** | |
| **Cabin of 3D printed curiosities. 2018.**<br>*Innovating materials for large scale additive manufacturing: Salt, soil, cement and chardonnay* [82]. Emerging objects. Glazed 3Dprinted ceramic cladding system that serves as a rain screen. |  |

(*continued on next page*)

**Table 2** (*continued*)

| Description | Image |
| --- | --- |
| **New Delft Blue. 2019.** *New Delft Blue* [90]. Studio Rap. Glazed ceramic tiles manufactured with material extrusion. |  |
| **TECLA. 2021.** *TECLA Technology and Clay 3D Printed House* [84]. Mario Cucinella Architects, WASP. House built with raw earth in a material extrusion process. |  |

fabrication challenges. High deformation is a predominant issue because of the water content and post-processing firing temperatures. For instance, shrinkage of the elements is a challenge due to water evaporation during material drying or sintering, which in turn leads to sample deformation and even cracking. The cracking of non-sintered clay constructions can be solved by filling the gaps; however, this process requires post-processing. For facade application, watertightness is required in specific climates, which limits the use of clay-based materials. Additionally, printing-induced defects, such as air inclusions in printed beads, reduce the structural performance of the printed object compared to conventional (e.g. rammed) elements. However, controlled air inclusions potentially have a positive impact on the thermal resistance of the printed component. 3DP of clay-based materials can be used for specific applications, to achieve environmentally friendly facade systems. Sustainability plays a key role in building 3DP clay-based facades. These materials are advantageous due to their recyclability and minor negative environmental impact. However, the challenges in the fabrication process require further exploration that can be overcome by investigations on deformation control, tensile strength optimization, and material response to the environment. Future possibilities can rely on using multiple clay body types, on making functionally-graded materials with a dual-material nozzle and adding a fourth axis to the 3DP setup [95].

### 3.3. Concrete

In the past two decades, 3DP of concrete has gained increased attention from the research community as well as industry. The maturity of this 3DP method is showcased by the high number of start-ups (e.g., Xtree, Aeditve, COBOD, WASP) and construction companies focusing on this specific part of 3DP for AEC, such as PERI, and SIKA. Concrete can be 3DP using different approaches like extrusion-based 3DP, shotcreting, casting concrete in 3DP formwork, selected cement activation, or 3DP of foamed concrete [96]. A comprehensive overview of different fabrication methods of concrete 3DP can be found here [97]. The environmental impact of concrete 3DP is largely defined by its binding agent [98] and the construction scheme used [99]. High cement contents in 3DP concrete increase the embodied energy of the printed object, and therefore, alternative binding agents are investigated [99]. In parallel, the potential of recycled aggregates is explored [100,101].

Major research topics of 3DP concrete, like reinforcement and challenges in regards to scaling up the process, have been investigated in depth by [102–104]. Over the past years, different trajectories for reinforcing 3DP concrete structures have been investigated. For extrusion-based concrete printing, those range from embedding a metal wire within the bead while printing [105], or shooting metal clamps through printed layers [106]. As an alternative way to 3DP concrete, shotcrete has proven to incorporate regular rebar and create load-bearing elements in an automated manner [102]. However, its application compared to extrusion-based processes is low. Bos et al. have concluded that the structural application of extrusion based 3DCP elements is still limited due to the lack of regulatory and limited options for reinforcements [107]. Therefore, contemporary projects mainly focus on either, using 3DCP elements as lost formwork for regular reinforcing and casting, or creating unreinforced masonry structures.

As concrete 3DP technology becomes more mature, the control over fabrication parameters is improving, researchers recently investigated topics that go beyond the free-form design and structural integrity of the facade component, see Table 3:. For facades application, thermal resistance, sound insulation, and absorption are performances of great relevance. Research on these topics is summarized in the following paragraphs.

Different research trajectories have been investigating the thermal performance of 3DP concrete or how to thermally insulate the 3DP building component. For extrusion-based 3DP concrete, two main strategies are identified: i) cladding the finished component with insulation material, and ii) filling up the internal cavities with insulation material. The KampC-House showcases both examples in a real-world application [108]. In addition to that, Bard et al. [109] introduced 'thermal design' within the robotic construction of building components by connecting the behavior of airflow and heat transfer with robotic tool-path planning. The researchers used the process to prototype the surface geometry of concrete facades to tune heat absorption, storage, and dissipation. The process combined measured thermal data and simulated input with robotic manufacturing techniques. 3DP polymer foam can be used as a lost formwork for cast concrete, as a load-bearing approach for insulating facades [110]. A similar approach is used by Furet et al. and the company Batiprint3d where a mobile robotic arm sprays foam as a lost formwork on the construction site [96]. However, the potential health risks connected to the organic foam of these methods require an investigation of alternative solutions, such as inorganic foams [111]. Adams et al. demonstrated how concrete can be foamed in a shotcrete-3D printing approach. The research successfully identified that a concrete foam with a density of only 150 kg/m3 can be applied to vertical surfaces [112]. Although this ultra-lightweight foamed concrete mix displays good thermal performance and fire resistance, the material strength is very low and thus not suitable for facade application. Another approach to increase the thermal resistance of 3D-printed concrete is the use of lightweight additives. The research from Liu et al. used expanded perlite to replace sand in the dry mix shotcrete [113]. They proved that 75% sand substituted with expanded perlite aggregate offers superior thermal properties without compromising its mechanical performance. Additionally, Henke et al. used perlite or wood aggregates to create lightweight mixes for extrusion-based concrete 3D printing [114]. Dielemans et al. investigated cellular geometries as thermal insulation for 3Dprinted concrete structures by using a design workflow that includes geometric, material, and fabrication parameters. The authors used 2d (conduction and radiation) heat transfer models and concluded that cell partitioning along the heat transfer direction improves thermal insulation by limiting convection even if the air-solid ratio decreases [115]. Similar to this research, on how the geometrical features of 3DP concrete can increase thermal resistance, Prasittisopin et al. investigate how geometrical differentiation improves acoustic properties [116]. However, this research trajectory seems to offer only limited applicability, as sound absorption can only be achieved for specific frequencies. Further research is needed to understand and improve the acoustic properties of 3DP concrete.

To conclude, concrete 3DP has the potential to create bespoke facade

**Table 3**
Concrete 3DP for facade application.

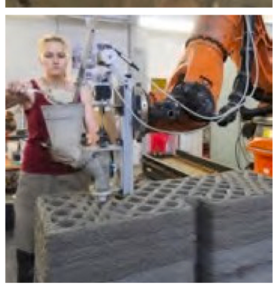
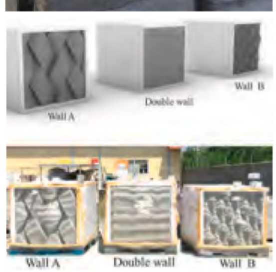
| Description | Image |
|---|---|
| **Research Projects** | |
| **3DP foam for cast concrete. 2017.**<br>*Towards site-specific and selfsufficient robotic fabrication on architectural scales* [110]. Mediated Matter Group, MIT Media Lab, Massachusetts Institute of Technology. Robotic on-site 3D printed foam as lost-formwork for concrete. |  |
| **Robotic concrete surface finishing. 2018.**<br>*Robotic concrete surface finishing: a moldless approach to creating thermally tuned surface geometry for architectural building components using Profile-3D-Printing* [109]. Carnegie Mellon University. Prototyping concrete surfaces to tune heat absorption, storage, and dissipation. |  |
| **Foamed 3DP Concrete. 2019.**<br>Ultra-lightweight foamed concrete for an automated facade application [112]. RWTH Aachen. Development of ultra lightweight foamed concrete (150kg/m3) for spraying/ extruding onto vertical walls. |  |
| **3DP of lightweight concrete. 2020.**<br>*Additive Manufacturing by Extrusion of Lightweight Concrete Strand Geometry, Nozzle Design and Layer Layout* [114]. Technical University of Munich. Investigations of nozzle design, layer layout for lightweight concrete extrusion. Addition of perlite and wood particles to improve thermal resistance. |  |
| **Thermal and sounds isolation of 3DPC. 2020.**<br>*Thermal and Sound Insulation of Large-Scale 3D Extrusion Printing Wall Panels* [116]. SCG Cement, Bangkok. Investigation on thermal and acoustic insulation of 3D concrete printed wall elements. |  |
| **Shotcrete 3D Printing. 2020.**<br>*Shotcrete 3D Printing Technology for the Fabrication of Slender Fully Reinforced Freeform Concrete Elements with High Surface Quality: A Real-Scale Demonstrator* [117]. Technical University of Braunschweig. Fully reinforced, largescale demonstrator created using shotcrete 3D printing. |  |

**Table 3** (*continued*)

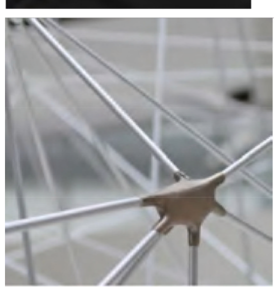
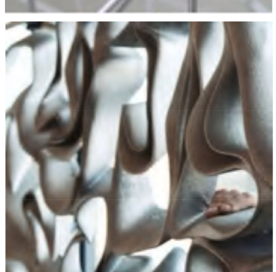
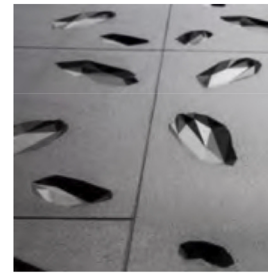
| Description | Image |
|---|---|
| **Thermally enhanced lightweight concrete wall. 2021.**<br>*Additive Manufacturing of Thermally Enhanced Lightweight Concrete Wall Elements with Closed Cellular Structures* [115]. Technical University of Munich. Closed cellular infill structures for a thermal performant 3DP concrete facade. Customization with 2D thermal performance simulation. |  |
| **Applied Research Projects** | |
| **3DP foam for cast concrete. 2019.**<br>*3D printing for construction based on a complex wall of polymer-foam and concrete* [96]. University of Nantes. Robotic foam 3D printed formwork. Deviation measurement and real-world demonstrator. |  |
| **On-site concrete 3DP. 2020.**<br>*3D Concrete Printing on Site: A Novel Way of Building Houses* [108] Ghent University, Beneens Construction & Interior, Saint-Gobain Weber Beamix. 3D printed house with different insulation strategies. |  |

components. Major improvements in process and material development have made it possible to create components at an architectural scale. Nevertheless, façade relevant topics, such as thermal and acoustics comfort, have not yet been sufficiently investigated. The manufacturing parameters of the printed component, as well as the assembly details, have a great impact on acoustics performance. The physical separation of single 3DP components needs to be investigated to holistically tackle this topic. For this reason, the topic of connections and how to accommodate thermal expansion and air-water permeability requires further investigation [118]. Nevertheless, the potential 3DP concrete for facade applications confines in successfully combining the displayed research examples. For example, a fully reinforced shotcrete wall element [117] can be combined with lightweight, thermally insulated shotcrete layers [113] that not only increase the thermal performance but have the potential to increase sound absorption and improve indoor comfort. Additionally, the fabricated geometry can be designed to enhance the thermal performance [115] to create a high-performance bespoke facade element.

### 3.4. Metal

Metal 3DP has been progressively adopted in the construction, biomedical, aerospace, automotive, and marine industries [119]. For this technique, metal and alloys are usually used in powder or wire form [21,120]. These materials are melted by a high-energy source in a layer-by-layer deposition to form a solid part. For Metal 3DP different processes can be used. The most notable techniques are powder bed fusion, direct energy deposition (DED), binder jetting, sheet lamination, material extrusion, and stereolithography [121], For large-scale fabrication, several projects have displayed the potential of metal 3DP, with DED as one of the widest-used techniques. For example, NASA 3DP with DED, a

**Table 4**
Metal 3DP for facade application.

| Description | Image |
|---|---|
| **Research Projects** | |
| **Tensegrity node. 2015.** *New Opportunities to Optimize Structural Designs in Metal by Using Additive Manufacturing* [129]. Arup. Comparison between a traditional node in galvanized steel, and a 3DP one made from maraging steel. |  |
| **Nematox II. 2016.** *AM Envelope: The potential of Additive Manufacturing for facade construction, Architecture and the Built environment* [14]. Delft University of Technology. Printed nodal point in aluminum for bespoke glass windows. |  |
| **The Spider Bracket. 2016.** *The Spider Bracket: A Topology Optimization Project by Altair,* Materialise *and Renishaw* [31]. Topologically optimized bracket manufactured with laser melting process. |  |
| **Bespoke node. 2017.** *3D metal printing as structure for architectural and sculptural projects* [127].3DP connectors for articulated glass panels in a facade. |  |
| **3D Printed Space Frames. 2018.** *3D Printed Space Frames* [126]. Singapore University of Technology and Design, Massachusetts Institute of Technology. 3DP nodes with tags to facilitate an easy assembly process. |  |
| **Cast Alu in 3DP mold. 2019.** *Bespoke Cast Facade: Design and Additive Manufacturing for Aluminum Facade Elements* [131]. ETH Zurich. Aluminum poured in a 3D printed sand mold for facades. |  |
| **Applied Research Projects** | |
| **Facade inserts. 2019.** *3D-Printed bespoke façade* [133] FIT Additive Manufacturing Group. Façade panel inserts customized by 3DP. |  |
| **Alu 3DP nodes. 2020.** *Design to Manufacture of Complex facades* [128]. Lithium Architects GmbH. N-AM Li3 project component test – Steel construction connected to the N-AM Li3 node. |  |

rocket thrust chamber, as part of the Rapid Analysis and Manufacturing Propulsion Technology project [122]. MX3D manufactured a metal bridge with wire arc additive manufacturing (WAAM), which is also a DED technique [123]. Similarly, Roland Snooks, together with RMIT Architecture Tectonic Formation Lab and FormX Technology, fabricated with WAAM a large-scale metal installation [124]. Nevertheless, these AM large-scale developments have not yet been used to fabricate facades.

For facade application, metal 3DP has been mostly investigated for the fabrication of small-scale elements and nodes of bespoke curtain walls, see Table 4. Nodes are essential facade elements with high structural demands. The metal 3DP process is advantageous for node manufacturing because of the free-form design potential of complex geometries with superior mechanical strength, resistance to fatigue and fracture toughness [125]. For this reason, in the last decade, metal 3DP nodes have been of particular interest to industry and academia [126,127]. For example, the Nematox node has been designed for critical zones of bespoke facade geometries where high mechanical strength is required [14]. Li3 Lithium Designers GmbH has been developing topologically optimized 3DP metal nodes for custom facade-systems designs [128]. These nodes have been augmented through topology optimization by distributing the material where it is required and creating lightweight parts. Others also used topology optimization by enabling a free-form design that responds to structural loads [31,129].

However, there are multiple challenges for metal 3DP processes. For example, powder-based 3DP techniques suffer from limited component size, a slow fabrication time, and high material prices [130]. Although stereolithography or digital light processing are high-precision techniques, they require postprocessing and have a small build volume [131]. Direct energy deposition, such as wire arc-based technique, can potentially facilitate large-scale components [132]. For the application of facades, metal large-scale manufacturing is challenging and relies heavily on material properties and fabrication constraints. For this reason, there have been scarce investigations on large-scale Metal 3DP facades. A cost-effective material with lower porosity would be advantageous with a deposition strategy to prevent cracking, delamination, swelling, and warping [121]. Additionally, the post-optimization steps of facade nodes require high level and time-consuming computational skills [129]. This is because the optimization process is not entirely automated. A human operator usually investigates the quality control of these metal parts and modifies them accordingly throughout the entire design-to-fabrication process. The Bespoke Cast Facade is a rare example of a large-scale cast aluminum structure in a 3DP sand mold [131]. Current investigations of metal 3DP facades are still in development and require quality control. The lack of standardized guidelines and practices limits the validation and reliability of these results.

To summarize, metal 3DP has been mostly investigated for bespoke nodes, as it offers excellent opportunities for structural elements. These materials have a high degree of recyclability, compared to polymers, concrete, and ceramics [134]. Additionally, free-form design and topology optimization facilitate the fabrication of efficient and custom-tailored features. Nevertheless, 3DP of large-scale facade components are still in its infancy. Further investigation is required to implement large-scale 3DP nodes in real-world case scenarios. Such as building elements that integrate well with 3DP facade nodes and would create added value in terms of environmental performance and CO2 footprint. However, as the commercialization of WAAM advances, the authors see the potential for durable and bespoke large-scale metal facades.

### 3.5. Alternative processes

This section presents experimental materials and fabrication techniques that, although relevant for facade application, are still in an early stage of development and have not reached an architecture-relevant scale. Such limitations indicate that these processes fall in the category of future potential rather than an applied facade fabrication technique. The alternative methods of this section include glass 3D printing, self-healing [135], self-cleaning [136] CO2 capturing [137] and shape-memory materials (SMM), see Table 5. Generally, SMM, also known as smart materials, are the materials investigated the most and have been classified as 4D printing processes. SMMs respond to various actuation mechanisms, such as pre-tension [138], or changes to moisture, temperature, light, current, or pH level [139–141].

#### 3.5.1. Shape memory materials

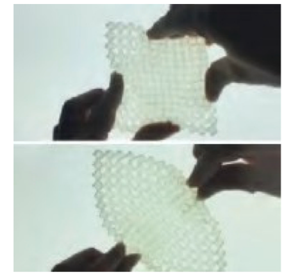
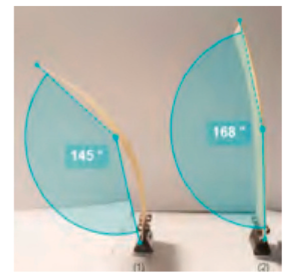
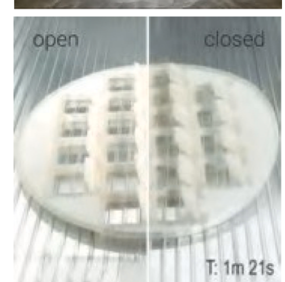
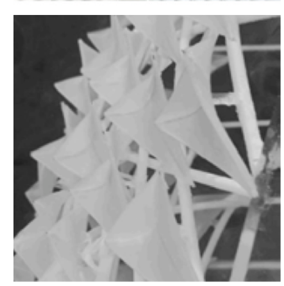
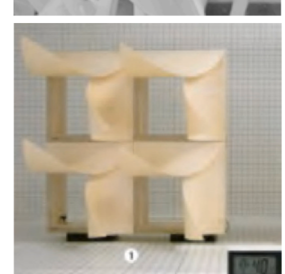
SMM processes have been investigated for facade applications due to their responsive behavior. It has been theorized that climate actuators can modify in real time the facade response to the environment, such as sun, humidity, wind, and temperature fluctuations, see Table 5. The manufacturing principles include design strategies towards material modification, and geometry amplification [141]. For example, Yi et al. investigated 4D printing for a climate-specific building skin. A two-way shape memory effect of the 3DP polymer was analyzed in a small-scale prototype, which demonstrated reliable reversibility of the shapeshift [142]. Another design potential for facade application is the 3D printing of polymers on textiles, creating active membrane elements and structures [138]. Dynamic shading for facades has been investigated using 4D-printed actuators that respond to various humidity levels [143,144]. The results prove the potential of self-actuated mechanisms for responsive facade designs.

SMM showcases a great potential for active climate-specific facades. However, there are significant challenges in regard to facade application, as SMM are typically less durable and relatively fragile [145]. Additionally, material reversibility to the original configuration becomes challenging after repetitive use. For this reason, future developments require a multidisciplinary approach to achieve the technological transfer from material science to architecture. Furthermore, advancements in materials and fabrication processes are essential to solve the issue of material degradation [146].

#### 3.5.2. 3D printing of glass

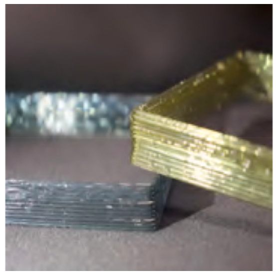
Despite the notorious difficulties in shaping glass due to the high temperatures required, it has been investigated as a material for 3DP [147]. 3D printing of glass comprises a variety of techniques: Stereolithography (SLA) and digital light processing (DLP), Selective laser sintering/melting, direct ink writing, and vat photopolymerization [148]. These techniques allow high-resolution fabrication of complex components for optical and microfluidic applications.

**Table 5**
Alternative 3DP processes for facade application.

| Description | Image |
|---|---|
| **Research Projects** | |
| **Heat-actuated auxetic facades. 2018.** *Heat-Actuated Auxetic Facades* [151]. Autodesk, Steinberg Architects. Auxetic patterns for reconfigurable shading elements in a facade. |  |
| **4DP hygroscopic actuators. 2018.** *4D printing of wooden actuators: encoding FDM wooden filaments for architectural responsive skins* [143]. Arab Academy for Science, Technology and Maritime Transport. 3DP wooden responsive actuators for adaptive facades with dynamic shading configurations. |  |
| **3DP glass. 2018.** *Additive Manufacturing of Transparent Glass Structures* [149]. Massachusetts Institute of Technology. Demonstration of novel largescale glass 3D printing technology through the design of 3-m tall columns. |  |
| **Thermoresponsive facade elements. 2019.** *SMP Prototype Design and Fabrication for Thermoresponsive Facade Elements* [152]. University of Seoul. Shape Memory Polymers prototypes are proposed in cell types for facade shading. |  |
| **4D-printed self-shaping building skin. 2021.** *Prototyping of 4D-printed selfshaping building skin in architecture: Design, fabrication, and investigation of a two-way shape memory composite* [142]. Ajou University. Design, fabrication, and investigation of a two-way shape memory composite facade panel. |  |
| **Hygroscopic actuators. 2021** *3D-Printed Wood: Programming Hygroscopic Material Transformations* [144]. *University of Stuttgart, Massachusetts Institute of Technology. 3DP custom wood grain structure to promote tunable self-transformation.* |  |

(*continued on next page*)

**Table 5** (*continued*)

| Description | Image |
|---|---|
| **3DP glass. 2022.** *Glass 3D Printing, MapleGlass Printing Ltd* [150] *MapleGlass Printing. Demonstration of commercializing recycled glass 3D printing technology.* |  |

Only recently, extrusion-based processes have been investigated to scale up to an architecturally relevant scale. Researchers from MIT demonstrated the capability of large-scale glass 3D printing through the fabrication of three-meter-tall columns assembled out of multiple large-scale components [149]. Maple Glass Printing [150] is an Australian company that also focuses on scaling up this technique and its commercialization. Their current 3D printer offers a build volume of 170 × 200 × 300 mm.

In the future, 3DP glass will hold great potential for the application of facades due to its mechanical strength and optical transparency. Still in its infancy, further research needs to investigate performance characteristics as well as improvements in the fabrication process to fully harvest its potential.

## 4. Performance assessment for 3DP facades

State-of-the-art research in 3D printing in architecture and construction demonstrates iterative workflows that integrate essential facade performances in the design process. The reviewed studies highlight the difficulties connected to integrating and measuring the performance metrics of 3DP facades. Irrespective of the material-technology combination, researchers and designers face similar challenges when it comes to quantifying the thermo-optical behavior, weather resistance, and durability of 3DP facades.

First of all, obtaining consistent performance results over a batch of 3DP components is usually a challenging task [18], for the difficulty in maintaining continuity and quality in the extrusion process [86]. Moreover, insufficient control over the rheological and hardening properties of the printing materials poses a challenge to the achievement of high performances [39]. This is even more crucial in ceramic manufacturing, as the sintering or curing process contributes to uneven shrinkage and microcracking of the elements. This brings limited predictability of the final outcome, contributing to challenges in standardizing 3DP ceramic parts for performance assessment. Moreover, the material type and mix play an essential role in thermal conductivity characterization. Thermal performance simulation of 3DP cellular structures requires an understanding of the multiple heat transfer modes within porous geometries. It needs to include the modeling of 3-dimensional buoyancy-driven heat transfer and its validation through experiments [115]. In the study of insulation and thermal bridging, the effect of printing parameters, such as layer thickness and height, has not been sufficiently researched [115,153]. Regarding solar and daylighting properties, specifically thermoplastics, the relation between printing settings, geometry, and performance needs to be investigated [61–63]. In this direction, Seshadri et al. [154] propose a data-driven characterization of the optical performance of 3DP facades to be embedded in a parametric design tool for building facades. However, there is still a lack of understanding of the effects of fabrication parameters on optical properties and the interaction of thermal and optical domains.

The application of standardized durability and weather-tightness testing procedures to 3DP facades is in its infancy. Preliminary and short-term accelerated testing has been performed, and observed UV degradation of 3DP polymer samples [62,65]. Due to the lack of built examples, however, standardized testing of full-scale prototypes is also required to obtain representative results for the expected service life of 3DP facade components. In general, the effects of coating and post-processing to achieve weather resistance have not been sufficiently addressed [63,65].

### 4.1. Performance indicators and standards

The performance characterization of digitally fabricated facade components poses a series of challenges. First, the simplified models prescribed by facade standards (e.g., ISO 6946, ISO 10077-12, and ISO 15099) cannot fully be applied to complex and bespoke geometries [155,156]. Furthermore, the standard averaged performance indicators, such as u-value or solar heat gain coefficient (SHGC), are not able to capture the heterogeneous and site-specific properties that 3DP facades can exhibit [157]. Secondly, as no specific fabrication standard has been established for 3DP facades, complying with existing norms is a challenge, and extensive testing is required [118]. This can mean a huge effort when bespoke geometries are involved, and it is often not feasible to test all the different specimens. Therefore, a combination of analytical, computational, and experimental methods should be used for effective performance assessment. Such an approach has not been found in most of the reviewed studies, and the development of general methodologies of performance assessment of non-standard facades [158] holds great potential for 3DP components.

Besides performance capabilities, environmental impact is becoming a crucial aspect in facade design [22,159]. The application of LCA to 3DP building components is currently at an early stage. However, some studies reveal that the fabrication process itself contributes minimally to the overall environmental impact of the components [19]. Material production has the highest environmental impact and, therefore, reduction in the amount of material use and embedding multiple functionalities in a single component are critical strategies [19,160]. In light of this, there have been efforts towards 3DP of recycled polymers with built examples relevant to the building scale [161,162]. However, none of the reviewed studies addresses the assessment of operational emissions of spaces or buildings equipped with such components, which would clarify the impact of hybrid and tailored performances in the use phase of these components [163]. A comprehensive assessment of building facades, and 3DP ones, should include environmental impact indicators. Additionally, there is a growing research interest in the social and economic implications of 3DP in relation to business models, labor market, and working conditions [164].

### 4.2. Need for new modeling approaches

As presented in the previous section, the challenges of performance assessment of 3DP parts connect to the complex interactions between material, geometry, and fabrication. On the first level, the properties of the 3DP materials are affected by the fabrication process. The extrusion and subsequent layered deposition of material cause changes in material properties and anisotropy, so the thermal, mechanical, electrical, and optical behaviors of the 3DP material differ from those of the solid one [165,166]. Furthermore, AM-induced geometrical irregularity can have important effects on their mechanical behavior [167,168]. For 3DP facades, structural anisotropy has been widely investigated, and different studies show how to account for this in the design of the components [9,74,169]. The effect of fabrication parameters on other properties such as thermal conductivity [170], optical properties [171], and electrical insulation [172] is mainly under investigation outside the building domain. Performance modeling of 3DP facade components could greatly benefit from the adoption of well-established methods from other fields, such as automotive, aerospace, and material engineering. Fabrication-induced material behaviors and properties are often investigated through experimental campaigns. Small-scale material samples are fabricated and tested to obtain material properties databases [173,174]. Moreover, experimental data can be used to train generative statistical models allowing for structural performance predictions for AM steel, at higher dimensional scales [175]. Another approach is the simulation of the 3DP process by means of computational fluid dynamics (CFD) and finite element (FE) simulation. It was shown that the numerical study of the rheological behavior of the printing material and its hardening is key to understanding the properties of 3DP parts [176,177]. At the component level, the 3DP material behavior and the geometry-dependent properties need to be simulated. This is a common challenge when designing infill porous structures, and TO components [28,31]. In contrast to traditional standardized facade components, 3DP ones often exhibit heterogenous properties [67,68]. Therefore, the validation of numerical models is done through testing of large-scale components [116,155].

Multiscale modeling is a commonly used approach in engineering to bring together the physical phenomena that occur at various dimensional scales in 3DP components, and enable the designer's control over the entire process [178]. This approach is based on the simultaneous modeling of the physical phenomena occurring at the material and component level and bridging between the scale by means of homogenization, averaging techniques, and statistical analysis, among others [179]. Over the last decade, multiscale approaches to modeling have reached maturity for 3DP metal parts [180] and accelerated the establishment of metal 3DP for fabricating functional parts. The authors believe that this approach would be beneficial to improve the fundamental understanding of the behavior of 3DP components for facade applications and enhance their performance. Because of this new level of complexity, there has been little attempt at investigating the behavior of 3DP facades once applied to buildings. The lack of built examples and post-occupancy data makes it imperative to investigate each project's performance and durability aspects. At the same time, current building performance simulation (BPS) tools often lack the ability to account for interactions between physical domains, and spatial and time scales [13]. Building-scale performance assessment could be done in living labs where research buildings are used as a test-bed for the performance monitoring of innovative components [181–183].

## 5. Discussion and conclusion

In this chapter, we reflect on and discuss the different aspects of 3DP of facades reviewed in this paper. Over the last decade, research has focused on establishing large-scale 3DP processes in the AEC sector using different technologies, resulting in general public awareness, investments of established construction companies in 3DP technologies, as well as the creation of start-ups. However, research related to 3DP facades is a novel topic, which has gained increased visibility in the past decade. To this date, few fundamental studies have tackled this topic, as most reviewed articles focused on demonstrating the 3DP facade fabrication potential. The performance aspects of these facades, like thermo-optical properties, need more in-depth, incremental research efforts. With similar effort, assembly details and installation requirements, such as panel-to-panel and panel-to-structure connections, need to be investigated. Therefore, this review provides a comprehensive overview of 3DP facades to guide novel research and identify future trends.

### *5.1. Design and performance assessment*

We have identified that most reviewed articles tend to establish project specific workflows and methodologies, as no comprehensive standardized design software, printing, or assessment tool exists to this date. Most of the research is conducted with in-house developed processes, including hardware, printing material, and software. This process results in a lack of a generalized database for researchers to compare material properties, printing settings, or performance measurements. With open-access databases, as for instances established for metal forming and composite materials, a closer collaboration between industry, academia, and regulatory authorities can be achieved towards the development of new building components. In line with this observation, none of the reviewed articles described the modification of the 3D printing process, or hardware, as well as material, for improving the performance of a 3DP facade and designers' control over it.

So far, performance-informed computational strategies, like topology optimization, are mainly found in the application of metal 3D printing for bespoke connections. Other facade-relevant attributes like thermal resistance and optical properties are not yet fully integrated into the design process considering environmental boundary conditions. Moreover, the use of infill structures and their influence on fabrication (e.g., printing time, weight) and performative aspects (e.g., U-value, SHGC, optical and acoustic properties) are not investigated sufficiently yet.

### *5.2. Fabrication maturity and potential commercialization*

Over the last few years, 3DP technologies have become more mature and commercially available. There is a tendency to move away from in-house developed 3D printing equipment towards commercially available systems, which was until now hindering the reproducibility and comparability of experimental results. Research can now focus on more facades-related research like material development, testing of weather resistance, or the aging behavior of 3DP objects. Additionally, the commoditization of large-scale 3DP equipment will allow for easier access and more research activities, which finally increase comparative studies and data sharing. The authors believe that this development will propel the research and commercialization of 3DP facade systems. 3D concrete printing is, until now, the only process that has successfully moved from academia to industry, which is reflected in the high number of companies and startups focusing on different aspects of 3DP concrete. Although researchers describe in detail the material characteristics and printing parameters for other 3DP methods, there is a lack of knowledge transfer from academia to the industry of those. In general, only a few companies provide general price market information and estimation of costs per square meter of 3D printed facade elements, or how many printers it would take to 3D print the entire facades of a building in a reasonable cost and time frame. The question of logistics or in-situ printing against pre-fabrication for the use-case of 3DP facades is not been sufficiently addressed yet.

The authors identified that the selected 3DP material defines the application scale and functionality of the 3DP facade, see Table 6. Polymers display ease of integrating multiple functionalities in a translucent element. Non-fired clay based materials are low-embodied energy alternatives for 3DP facades. Concrete shows great potential for large-scale in-situ fabrication. Metal 3D printing is mainly used for high-precision joining elements requiring mechanical strength.

### *5.3. Sustainability and impact*

The urgent challenge of decarbonization of the building sector is leading the construction industry towards more performative and sustainable building components and systems. The authors believe that 3DP can contribute to this transition by enabling site-specific, high-performance facade components with low environmental impact. Although the life expectancy of 3DP facades still needs to be assessed, several studies highlight the positive impact of monomaterial components, which can be easily replaced and recycled at the end of their life cycle. Moreover, as the 3DP construction sector develops, consolidation of recycling schemes and growing implementation of recycled material 3DP is expected. Comprehensive sustainability assessment methods should be applied to the 3DP components, combining environmental impact with economic and social sustainability. This would unveil the socio-economic aspects connected to a shift to 3DP building components in the construction industry, in relation to working conditions, safety,

**Table 6**
3DP facades advantages and challenges.

| Material/ Application | Advantages | Challenges |
|---|---|---|
| **Thermoplastics**<br>Facade elements/Panels<br>non-structural<br>transparent/ opaque<br>insulating<br>monomaterial<br>multifunctional | **Fabrication**<br>• adjustable resolution & high design freedom<br>• high buildup rate<br>**Performance**<br>• good thermal resistance<br>• low density/ lightweight<br>• recyclable<br>• diverse materials: translucent, opaque, reflective | **Fabrication**<br>• high shrinkage during fabrication<br>• overhangs need support<br>**Performance**<br>• low acceptance as a building material<br>• low fire resistance<br>• weather resistance needs testing;<br>• unknown long term material behavior |
| **Clay-based materials**<br>Walls/ Cladding/ Tiles<br>**Un-fired**<br>Structural/ non-structural<br>opaque<br>insulating | **Fabrication**<br>• suitable for large scale<br>• in-situ fabrication<br>• affordable<br>• sourced local<br>**Performance**<br>• reusable<br>• low environmental impact | **Fabrication**<br>• high crack sensitivity<br>• heavy equipment needed<br>• high deformation after curing<br>**Performance**<br>• low toughness<br>• brittle<br>• low weather resistance |
| **Fired**<br>weathering layer<br>non-structural<br>non-insulating | **Fabrication**<br>• suitable for small to mid scale<br>**Performance**<br>• good weather resistance<br>• good compressive strength<br>• durable | **Fabrication**<br>• additional firing process<br>• high deformation after firing<br>**Performance**<br>• difficult to recycle<br>• no structural applications |
| **Concrete**<br>in-situ 3DP walls<br>stay-in place formwork<br>structural/ non-structural<br>opaque<br>non-insulating<br>multifunctional | **Fabrication**<br>• large-scale components<br>• high industry adaptation<br>• high buildup rate<br>• different approaches for 3DCP available<br>**Performance**<br>• fire resistant<br>• good compressive strength<br>• durable | **Fabrication**<br>• low resolution limits design freedom<br>• postprocessing to meet surface finish standards<br>• heavy equipment needed<br>**Performance**<br>• low thermal resistance<br>• additional reinforcement needed<br>• high cement content increases $CO_2$ footprint<br>• high density /heavy weight |
| **Metal**<br>structural nodes<br>structural<br>monomaterial | **Fabrication**<br>• standard: high resolution, detailed and complex geometry<br>• WAAM: low resolution for mid to large-scale parts<br>**Performance**<br>• structural strength and ductility<br>• recyclable | **Fabrication**<br>• standard: small build size, high costs & fabrication time<br>• limited resolution (WAAM)<br>**Performance**<br>• high density /Heavy weight<br>• high thermal conductivity |

employment patterns, and the role of users.

### 5.4. Conclusion

To conclude, although 3DP provides the opportunity to create site-specific designs, the review revealed that, to the present date, this potential mainly remains untouched. The question of true added value of 3DP for the application of facades remains open, as the potential benefits need to face the challenges in regards to scalability and economic viability. The authors believe that this lack of development is due to the fact that large-scale 3DP methods only recently became available to a broader audience. Furthermore, facades are among the most complex building components, and, thus, difficult to be extensively investigated within single research projects. Therefore, the authors identify the need for a multidisciplinary research approach and collaborations, as well as large-scale demonstrators that bring together expertise on computational design, digital fabrication, material development, and performance assessment. More fundamental research is required to understand the relationship between fabrication constraints, material behavior, and computational design. A thorough understanding of these aspects will allow 3DP facades to move from prototypical demonstrators to viable solutions for the building industry.

## Author contributions

M.L., I.C., and V.P. contributed equally to this paper. Conceptualization, M.L., I.C., and V.P.; investigation, M.L., I.C., and V.P.; writing—original draft preparation, M.L., I.C., and V.P., and B.S.; writing—review and editing, M.L.,V.P. and IC; visualization, M.L., I.C., and V.P.; B.D., F.G., M.K., and A.S. supervised the project and manuscript conception. All authors have read and agreed to the published version of the manuscript.

## Declaration of Competing Interest

The authors declare that they have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

## Data availability

No data was used for the research described in the article.


## Acknowledgement

This research is financially supported by the National Centre for Competence in Research in Digital Fabrication, funded by the Swiss National Science Foundation (NCCR Digital Fabrication Agreement number 51NF40141853).

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