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# Multi-material additive manufacturing in architecture and construction: A review

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ABSTRACT

Multi-Material Additive Manufacturing (MMAM) is an emerging manufacturing approach that is gaining interest in architecture and construction as an expansion of Additive Manufacturing. Hereby, different materials or material properties are combined in a single additive process in order to create objects that are composed of multiple materials. Ultimately, this approach introduces a new way of manufacturing and building, where assembly is no longer a necessity in order to combine multiple materials. Moreover, different potentials can be derived from the use of MMAM. Leading towards components with heterogeneous material composition and a high degree of adaption towards structural, environmental, and design criteria. This work provides an overview of the current state of MMAM in architecture and construction. Different processes and materials which have been reported are discussed and potentials, which emerge through the use of MMAM are described using specific use-cases.

## 1. Introduction

The construction industry is facing major challenges resulting from high material and energy consumption on the one hand [1,2], and from almost stagnating productivity growth on the other. A study published in 2017 by the consulting firm McKinsey, revealed that the annual productivity growth in construction has increased by an average of only 1% over the past twenty years. This compares to 3.6% in general manufacturing and 2.8% for the total world economy, [3,4].

While buildings are becoming increasingly complex to meet the goal of climate neutral buildings and the associated increasing demands on building performance [5], construction methods have evolved only to a limited extend. Much of the construction work is still carried out in a labour-intensive and inefficient manner [3]. In addition, a number of problems are associated with prevailing construction methods, such as a high susceptibility to construction errors due to poor communication between the planning and the execution as well as high construction tolerances and the associated effort to align components accordingly [3,6,7]. On top of this, an increasing shortage of skilled workers and high risk for occupational diseases and accidents at the construction site place an additional burden on construction activities [3,8–10].

Digital fabrication technologies, and in particular large-scale Additive Manufacturing (AM) offer new opportunities to address these challenges. Optimized material use through topology optimisation [11–13], increased cost-effectiveness of the building process

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[13], and reduced reliance on labour-intensive work in line with higher work safety [14] are some of the emerging opportunities that can be exploited through AM. Yet, the majority of approaches in large-scale AM are limited to homogeneous materials and focus mainly on the load-bearing capacity of the printed object [15]. Further aspects of a building, such as building physics or technical installations, thus remain largely unaffected. Consequently, construction steps that address these aspects must be carried out in a conventional manner.

At the same time, most AM processes have the ability to combine multiple materials or material properties in a single process [16]. This approach, commonly referred to as Multi-Material Additive Manufacturing (MMAM), can introduce significant changes to current manufacturing and construction methods. Unlike traditional construction methods, which rely largely on the assembly of single materials or elements, AM with multiple materials enables the creation of objects with different material properties without the need for subsequent assembly. Ultimately, this change can address inefficiencies in manufacturing and construction by reducing the number of production steps required while providing solutions to problems that are associated with connecting individual materials or elements [17,18].

Moreover, the change from single-material to multi-material processes not only adds benefits for the manufacturing and construction process itself, but also entails extensive changes in regard to the design potential. The architect Tom Wiscombe describes this potential as “being able to not only customize structural rigidity but also create variable material responses to structural, environmental and aesthetic criteria all at the same time” [19]. In other words, this extends the design scope by allowing to alter the material properties across a single object and thus locally adjust the material to a whole set of different criteria. Ultimately, this change opens up the possibility for more sustainable constructions by reducing the material consumption through optimized material usage, and greater adaption of individual components to environmental criteria.

While research on single material Additive Manufacturing in architecture and construction has been ongoing for more than a decade [15,20–23], the implementation of multi-material processes is still fairly new. Despite the inherent potential of most AM processes to use multiple materials or material properties, only limited research exists on the implementation of this approach in the field of architecture and construction. As a result, the use and application of MMAM in architecture and construction remains largely unclear. At the same time, developments of MMAM in areas outside architecture and construction show compelling potentials of this approach [24,25]. In light of this development, a comprehensive review of MMAM in architecture and construction is needed.

To achieve this goal, the research first provides foundation knowledge on AM and MMAM. Subsequently, a structured overview of current processing methods in line with related materials that are used for implementing multi-materiality for architecture and construction by means of AM is given. This overview enables to define the field of approaches and to identify existing gaps. In addition, emerging potentials of the application of MMAM in architecture and construction are discussed along specific use-cases. Ideally, this review serves as a starting point for the development of new approaches and applications of MMAM in architecture and construction.

## 2. Methodology and structure

This review is structured in three main sections. a.) A broad overview on the topic of MMAM and adjacent areas will be presented in the first section. b.) This is followed by an in-depth review of current MMAM methods, used in Architecture and Construction, and c.) a review of MMAM applications and the related potentials. Finally, the review ends with a concluding section where possible outlooks are presented.

a.) A more detailed definition as well as a broad overview of methods for creating multi-material objects by means of AM is provided in section 3. This overview is based on recent review publications on MMAM, which are not solely based in the field of architecture and construction. The intention of section 3 is to introduce the reader into the topic, and provide a broader overview of potential methods, including methods that have not yet been tried and tested for an application in architecture and construction.

b.) Section 4. forms the main body of this study and was conducted through a literature review of research articles on MMAM processes applied in the field of Architecture and Construction. Therefore, using the online scholarly database sources Scopus and ISI Web of Science, as well as books and conference proceedings, related to the found publications. Key words used for this search are pointed out in Table 1. Publications containing a combination of these in the title, abstract, and keywords were

**Table 1**
Keywords and boolean operators used for the initial search.

| Material Concept | “AND” Processing Method | “AND” Field of Application |
|---|---|---|
| Multi-material* | “3D Printing” | Construction |
| Multiple material* | “3-D Printing” | Large-Scale |
| Heterogeneous material* | “3D-Printing” | “Large scale” |
| Varying material* | “Additive Manufacturing” | Architecture |
| Variable material* | “Digital Fabrication” | Building |
| Graded material* | “Rapid Prototyping” | |
| Gradient material* | | |
| Graduated material* | | |
| Variable property* | | |
| Varying property* | | |

considered. Subsequently, the findings were scanned and filtered in order to retrieve the most relevant articles for this study. The selection of relevant articles is limited to projects which either develop or adapt already existing methods for creating objects with material or property variation across their volume and are located in the field of architecture and construction. The results were categorized and described in the form of a detailed overview.

c.) A discussion about potentials which can be gained by applying such methods in architecture and construction is provided in section 5 of this review. These potentials were retrieved from practical applications with reference to the MMAM processes and materials described in section 4.1 and 4.2. Furthermore, these potentials are discussed with regard to the opportunities in architecture and construction on a more general level. The selection of applications is based on the conducted literature review. More precisely, on applications presented in the reviewed literature, and on references derived from it. A total of 14 projects on multi-material building components and building materials were selected for this overview, with varying degrees of maturity and different use-cases within this field.

In addition to that, current developments in AM were investigated by retrieving data from reports, published by stakeholders and governmental reports as well as review articles on the current state of AM in architecture and construction.

## 3. Towards a multi-material construction with additive manufacturing technology

Multi-Material Additive Manufacturing (MMAM) is a manufacturing method that allows to create objects with multiple materials or material properties across the volume of the object. For this review, the definition of MMAM processes proposed by Ref. [16] has been used to identify relevant publications and ultimately define the scope of this review. According to Gibson et al. the change in material composition via additive manufacturing can be implemented in three different ways.

- A process where two or more discrete materials are placed next to each other (Discrete Multiple Material Processes).
- A process where the material is processed in such a way, that the porosity of the final part is controlled though the processing method itself (Porous Multiple Material Processes).
- A process where the feed material is a blend of two or more different materials (Blended Multiple Material Processes).

Moreover, the ability to create such objects is a feature inherent to most Additive Manufacturing (AM) processes and can be achieved by either including more than one material, or by varying the properties of the respective material through modifying the processing parameters [25].

Compared to single material processes, AM with multiple materials has the potential to fundamentally change the way products or structures such as buildings are created. A key characteristic of most manufactured products or structures is that they are made of several different materials, with each material usually performing specific functions. In order to combine these materials, conventional manufacturing (including single-material AM) relies largely on the assemble of individual parts. In contrast to that, in MMAM different materials or material properties can be combined within a single manufacturing process. Consequently, the need for a subsequent assembly is omitted, as well as the associated restrictions. Ultimately, this approach allows for greater customization not only in terms of geometry, since individual parts no longer need to be designed to be assembled, but also in terms of material variations within a single object (Keating, S., 2014).

### 3.1. Additive manufacturing

The underlying process of AM plays a key role when it comes to implementing multi-material manufacturing methods to a wider range of applications, including large scale structures and components for architecture and construction. The ability to selectively place a raw material onto a building plate is a decisive reason for this. Since most AM processes operate either by a point by point or line by line processing method, these processes can potentially be extended with different materials. Thereby, allowing to incorporate multiple materials in a single build-up process and ultimately create objects with varying material composition without any form of assembly [16].

AM is a process which allows to create a physical object by deposing a material, usually layer upon layer, based on a three-dimensional Computer-Aided Design (3D CAD) model. The basic steps for this process are as follows [26]:

- Model making, creating a 3D model of the object through 3D CAD software or by using 3D-Scanning.
- Transforming the 3D model into an executable procedure for the respective 3D Printer. Typically, by cutting the model into 2D slices.
- The AM machine or more commonly 3D Printer, creates the physical object by depositing multiple material layers upon each other, based on the previously generated slices.
- After the printing process, the object has to be removed and can be post-processed.

Furthermore, a general definition of AM has been given by the American Society for Testing and Materials (ASTM): “a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to Subtractive Manufacturing and Formative Manufacturing methodologies”. Based on the ASTM definition, Additive Manufacturing processes can be categorized into seven different types of printing processes: Binder Jetting, Directed Energy Deposition, Sheet Lamination, Material Extrusion, Powder Bed Fusion, Vat. Photopolymerization, and Material Jetting [27]. A more detailed description of the individual processes is provided in section 3.3 of this review.

The term 3D Printing originated in the development of a particular AM process at the MIT, but has since become widely used. In this document, both terms are used with reference to ASTM's definition of Additive Manufacturing.

Compared to traditional manufacturing methods, AM offers several unique benefits. According to a survey on the state of AM by the 3D Printing service provider Sculpteo, the most applied benefits of AM are the possibility to create complex geometries, time saving through quick iterations and lead time reduction, cost saving, as well as the ability to produce mass customized objects [28].

Originally developed as a manufacturing method for rapid prototyping, current development is moving towards implementing AM as a technology for creating functional parts like end-use components which are ready to be used by the client or customers; tools and moulds for using in traditional manufacturing, and custom spare parts on demand; thereby shifting not only the way objects are developed, but also designed and manufactured. Ultimately, making AM a technology with highly disruptive potential [29]. This potential has already been recognised by a wide range of industries including automotive, aerospace, chemicals, healthcare and medical as well as high tech applications and consumer goods.

### 3.2. Additive manufacturing in architecture and construction

In line with this development, a similar development of AM can be observed in the field of architecture and construction. Building up on the early adopters of construction scale AM, e.g., Contour Crafting, 3d concrete printing and D-shape [30–32], development has evolved from experiments in a laboratory environment to the construction of real-world buildings with AM technologies. Since then, numerous initiatives joined this development and new projects are constantly pushing the boundaries of AM in construction in terms of material and process development [33,34,72,73] as well as design strategies and applications based on AM [35–37].

Moreover, a growing number of suppliers of large format 3D Printing machines for construction scale applications can be observed. According to the website aniwaa.com, which offers a comprehensive product database for 3D Printers, 3D Scanners, and AM Software, a total of thirteen different suppliers can be found at the moment of writing this review. With ten companies being listed as commercially available or offering a concrete printer prototype and three companies offering 3D Printing as a service [68]. In addition to that, more well-established construction companies are developing new products and services in line with 3d printing. For example, the company Peri, known as a supplier of formwork and scaffolding systems as well as engineering solutions, has recently included 3D Printing in their range of services [38]. A similar development can be observed at the swiss company Sika AG (Sika, n.d.).

Since the first research initiatives adopted the concept of AM in architecture and construction, the range of materials and manufacturing processes has increased considerably. In addition to concrete material, research was also conducted on the processing and application of metals, ceramics and polymer materials. Since then, numerous review publications have examined this development in more detail. However, according to these publications, a clear focus is set on concrete-based AM methods, mostly in combination with material extrusion processes [15,20–23].

Therefore, one conclusion is that in order to extending possible applications beyond load-bearing structures, it is necessary to continue the development and target a wider range of suitable materials and thereby material properties [15]. At the same time, it has been identified that slower production rates compared to traditional manufacturing poses a hurdle for the upscaling and implementation of already existing AM methods into a construction environment [20,22].

Moreover, overall benefits of AM can be applied on architecture and construction as well. A detailed and comprehensive overview of benefits from AM in connection with examples can be found in the publications of [15,20–22]; and [23].

The ability to process multiple materials simultaneously significantly extends this range of benefits. For instance, benefits such as

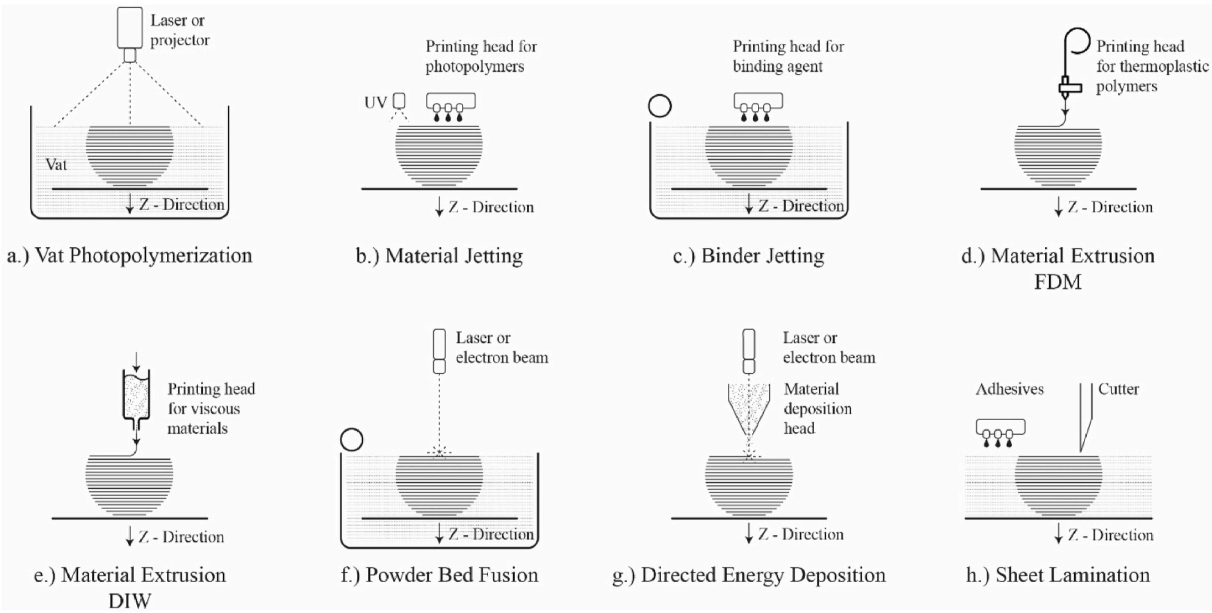


**Fig. 1.** Additive Manufacturing processes.

an optimized material usage through topology optimisation methods can not only be applied on a single homogeneous material, but also in combination with a range of different material properties.

Thereby, inevitably combining formerly separated parts and ultimately, integrating additive construction methods more deeply into the overall process of building construction [15,20,22].

### *3.3. Additive manufacturing with multiple materials*

Several published reviews on MMAM summarise the current development in this field. These reviews show that a wide range of AM processes have already been tested with the concept of multi-materiality. However, the level of maturity varies strongly in regard of the specific AM processing method. Ranging from already commercially available Multi-Material 3D Printing machines, like the Statasys Objet Connex series or multi nozzle filament printer, to processes which are still under development [25].

The following is a brief summary of AM processes described in the aforementioned reviews. These processes are categorized along the ASTM definition for AM processing methods. More detailed information can be found in the publications of [24,25]; and [39].

**Vat Photopolymerization** (Fig. 1a) enables the creation of objects with a high-quality surface finish and dimensional accuracy. Hereby, a liquid photopolymer is selectively cured by radiation. By using multiple vats, objects with multiple materials can be created. However, the use of different materials comes with the restriction to clean the object before using a different material, which slows down the printing process. The range of suitable materials is also limited to photopolymer liquids.

**Material Jetting** (Fig. 1b) uses inkjet printing technology in order to deposit selectively droplets of materials onto a platform. The solidification of the material is typically handled via cooling or UV light, depending on the used material. A multi-nozzle printing head deposits small droplet of material onto a building plate, whereby each nozzle is able to switch between different materials throughout the 3D Print. This printing technique is already commercially available among others by the companies 3dsystems and Stratasys. Common materials used for this process are photopolymer liquids and wax.

**Binder Jetting** (Fig. 1c), similar to Material jetting, is based on the inkjet printing technology. However, in contrasts to Material Jetting, a liquid binding agent joins a powder material, which is deposited layer wise on top of each other. Implementing multiple materials into this process is more difficult and only limited research has been reported by the afore mentioned reviews.

**Material Extrusion** describes a process were a material, which is either in a liquid state or transformed into a liquid state, is extruded through a nozzle and placed layer upon layer onto a platform. These two states form the two sub-groups that exists within material extrusion (Fused Deposition Modelling - FDM (Fig. 1d) which is based on melting a thermoplastic polymer and Direct Ink Writing - DIW (Fig. 1e) which is based on the extrusion of a viscous material). By using two or more nozzles simultaneously, multiple materials can be implemented. Multi Material Extrusion systems are commercially available either for Fused Deposition Modelling systems with multiple nozzles or for Direct Ink Writing machines. The range of possible materials includes different types of Polymers (Thermoplastic Polymers, Bio Polymers, and Resins), Concrete and Mortar, and Ceramic pastes.

**Powder Bed Fusion** (Fig. 1f) describes a process were a thermal energy source (laser, or electron beam) selectively fuses a powder material, which is deposited layer wise on top of each other. In order to combine several materials with this process, the powder layer must be created so that it consists of different materials. According to the review publications different methods have been already developed including a method for selective powder deposition by the Belgium company Aerosint SA. Polymer- (Thermoplastic), Metal-, and Ceramic-powders can be processed with this method.

**Directed Energy Deposition** (Fig. 1g) on the other hand uses powder material which is directly delivered from a material deposition head. This allows to alter the material continuously while delivering it from the head. Furthermore, a laser beam is used to melt the powder material immediately upon ejection. Due to the use of a powder feeding mechanism, the material can be changed or mixed when 3D Printing the object. Several types of this technology have been investigated, including Laser Engineering Net Shape (LENS), Laser Cladding (LC), and Direct Metal Deposition (DMD). These systems are used for metal, ceramic, and composite materials.

**Sheet Lamination** (Fig. 1h) is based on cutting and bonding multiple sheets of material in order to form a 3D object. To create multi-material objects, different sheet materials need to be used throughout the process. A subcategory of Sheet Lamination is Ultrasonic AM, which allows the processing and bonding of metal sheets via a welding method. Plastics, paper and metal sheets can be processes with sheet lamination.

Table 2 summarizes the variety of additive manufacturing processes with the ability to process multiple materials. However, transferring such processes into an architecture and construction environment needs further development. Similar to single material additive manufacturing, a limited printing volume, speed and resolution as well a material constraint need to be overcome in order to successfully transfer existing multi-material additive manufacturing methods from other disciplines into architecture and construction [15,23,31].

## 4. Relevant materials and processes for MMAM in architecture and construction

Although a variety of AM processes for applications in architecture and construction already exist, the vast majority of these processes are still limited to the production of objects with a single, homogeneous material. Clearly AM with multiple materials in the context of architecture and construction is at the very beginning. However, initial approaches are already visible and possible advantages or disadvantages can be discussed.

Therefore, this section will discuss how multiple materials or material properties have been implemented by means of AM to date. In this regard, the main group of AM processes is based on material extrusion. Here, an overview is given of different types of extrusion-based processes used for processing multiple materials or varying material properties in a single 3D Print. Besides, projects based on the material jetting technology can also be found. However, the related applications with the material jetting technology are largely

**Table 2**
AM processes according to the ASTM definition and related Multi-Material methods.

| Process category | Manufacturing principle | Multiple-Material method | Typical materials |
|---|---|---|---|
| Vat Photopolymerization | A liquid photopolymer is selectively cured by radiation. | Combining multiple vats in a single process | Polymers (Photopolymers) |
| Material Jetting | Droplets of material are selectively deposited layer wise onto a building plate. | Switching between different materials in the nozzle | Polymers (Photopolymers), Wax |
| Binder Jetting | A liquid binding agent selectively joins a powder material, which is deposed layer wise upon each other. | – | Polymer-, Plaster-, Metal-, Sand-, and Ceramic-powder |
| Material Extrusion | A material, which is either in a liquid state or transformed into a liquid state, is extruded through a nozzle and deposed layer upon layer onto a building plate. | Combining multiple nozzles or material feeding systems with different materials | Polymers (Thermoplastic Polymers, Bio-Polymers, Resins) Concrete, Ceramic pastes |
| Powder Bed Fusion | A thermal energy source (laser, or electron beam) selectively fuses a powder material, which is deposed layer wise upon each other. | Selective deposition of multiple powder materials bevor fusion | Polymer- (Thermoplastic), Metal-, and Ceramic-powder |
| Directed Energy Deposition | A focused thermal energy (laser, electron beam, or plasma arc) fuses materials by melting them during deposition. | Switching the respective material through the material feeding system | Metal-, and Ceramic-powder |
| Sheet Lamination | Sheets of material are successively shaped and bonded upon each other to form an object | Using different sheet materials throughout the 3D print. | Paper-, Polymer-, Metal-, and Ceramic-Sheets |

representative rather than working prototypes with the intention of a full-scale implementation and are therefore less in focus of this review.

### 4.1. MMAM processes

In material extrusion a structure is created by extruding a liquid or paste like material through a nozzle. Thereby, the nozzle follows a defined path and places the material layer-wise on top of each other. After the extrusion, the material has to bond with the underlaying layers of material and solidify. In this way, a physical object can be built up layer by layer from the material used.

Two basic principles, which are based on the type of material, subdivide this category. First, a process based on thermoplastic polymers. The heated nozzle melts the thermoplastic material and deposits it on top of a material layer or building plate. After the deposition, the material bonds with the underlaying layer and solidifies. Commonly, this process is described as Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF).

Second, after a liquid or paste like material is extruded by a nozzle the material solidifies through a curing agent, residual solvent, reaction with air, or by simply drying. Typical materials used for this process are, concrete or ceramic materials as well as different polymers [16]. Commonly, this process is described as Direct Ink Writing (DIW) or in combination with concrete material, Concrete Printing.

In construction scale AM, material extrusion processes have already been widely adopted in different variations and for different materials. The largest group of materials which are used with this system are concrete materials. Concrete is a well-known material in the construction industry and provides suitable material properties for buildings at a low cost. Most common processes for AM with concrete are Contour Crafting and 3D concrete printing [30,31].

In addition to concrete, polymer materials, more specific polyurethane, is also used in AM for the construction industry. This process is mainly applied to create a permanent, freeform formwork while at the same time utilising the insulating properties of the material. A fast-curing polyurethane is extruded for this purpose, which creates a closed-cell foam structure, that can be used as both, a formwork for concrete and the final insulation layer [40].

Furthermore, large-scale FDM processes are also applied in the field of architecture and construction. Possible applications of this process include façade panels, partition walls, or highly complex formwork elements [37]; Banyan Eco Wall 2019; Fast Custom Concrete, 2018.; [41].

In the following subsection, different approaches for using multiple materials are discussed. These are categorized according to how they are implemented with AM. A distinction can be made between AM processes that either process and deposit multiple materials in parallel (Fig. 2a), or AM processes that create a blend of different materials before deposition (Fig. 2d). Furthermore, within these

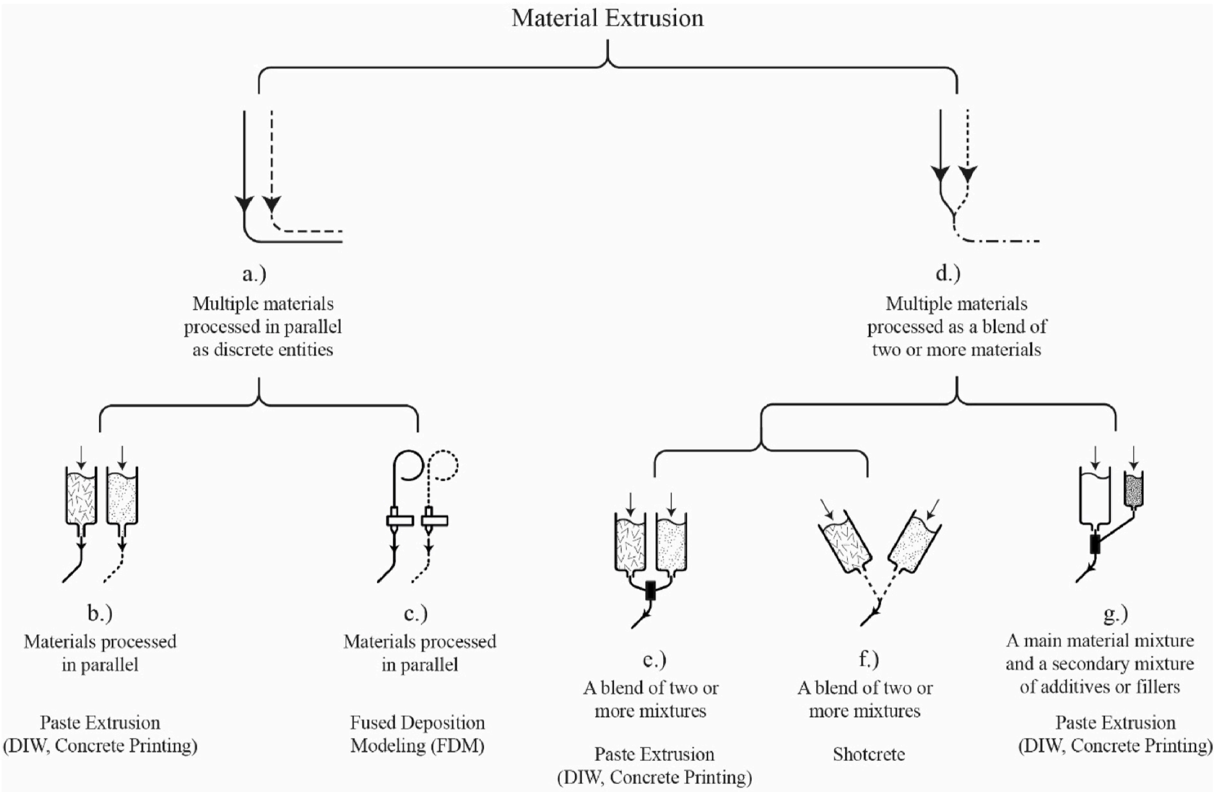


**Fig. 2.** Categorization tree for MMAM Processes in Architecture and Construction.

categories, processes can be further subdivided according to more detailed characteristics. Processes based on parallel extrusion, can be categorized into DIW and Concrete Printing processes (Fig. 2b) or FDM processes (Fig. 2c). Whereas processes that create a blend of different materials can be subdivided into processes where each individual mixture represents specific material properties and can also function on its own (Fig. 2e; Fig. 2f), and processes with a main material mixture and a secondary mixture of additives or fillers that can be selectively added (Fig. 2g).

#### 4.1.1. *Multiple materials processed in parallel, as discrete entities*

Systems which are composed of a multiplication of a single extrusion unit, can typically be described as a multi material process with parallel and discrete material outlets (Fig. 2a). These systems are usually composed of multiple material containers, feeding devices and material outlets. As a variation, the individual material outlets can also be connected to form a single outlet. However, no type of mixing will occur in these cases.

During the printing process, the respective material is selected as required and deposited according to the digital model. The material selection is usually limited to the same category of materials which allows for easy extension of the processing method with further materials. Thereby creating an expandable array of extrusion units.

Craveiro et al. presents an example of a setup with multiple outlets (Fig. 2b). More precisely, two premixed polyurethane polymers with different compositions are combined and processes in an AM system, equipped with two extrusion units. Thereby, this setup enables the creation of a single component, comprised of two different polyurethane compositions [42]. Another example is the Multi-Chamber Extrusion platform, developed by the Mediated Matter Group at the MIT. This research extends the concept of multiple, parallel extrusion units, by incorporating a wider range of different material mixtures and thus properties. Therefore, six individual material chambers are combined in a single additive manufacturing process. This allows to create objects that can exhibit a much wider range of material properties. More information about the specific properties that have been included can be found in section 4.2.2 [43,44].

**Table 3**
Summary of MMAM projects in architecture and construction – Categorized by manufacturing principles and materials.

| Material | AM Process | | | | | |
|---|---|---|---|---|---|---|
| | Material Extrusion | | | | Material Jetting | Other |
| | Concrete Printing | Direct Ink Writing (DIW) | Fused Deposition Modelling (FDM) | Shotcrete | | |
| Concrete | 3-D Printing Variable Density Concrete [47] | | | Functionally graded concrete [50,55,56] | | Concrete Fabrication by Digitally Controlled Injection (Chee et al., 2018) |
| | Graded Polystyrene Aggregate Concrete Structures [53] | | | | | |
| | 3D printing functionally graded concrete-based materials [48,49] | | | | | |
| | On-demand additive manufacturing of functionally graded concrete [54] | | | | | |
| Polymer | | 3-D Printing of U-V Curable Polymers with Variable Elasticity [46,47] | 3D-Printed Wood: Programming Hygroscopic Material Transformations [45] | | Chaise Longue Chair Gemini [57] | |
| | | Functionally Graded PU polymers [42] | We 3D Printed a Sensor with Conductive Materials [70] | | 4D Printing and Universal Transformation (Tibbits et al., 2014) | |
| | | Large-Scale Additive Manufacturing of Functionally-Graded Hydrogel Composites via Multi-Chamber Extrusion [43,44,58]; Duro.Royo et al. n.d) | | | Gradient Logics: The Durotaxis Chair [59] | |
| | | | | | Translating Digital to Physical Gradients [60] | |

In contrast to the projects, which are based on the extrusion of liquid or paste like materials, Correa et al. uses the fused deposition modelling (FDM) approach to deploy two different filament materials in a single 3D Print (Fig. 2c). A system comprised of two extruders allows switching between different filaments and thereby creating polymer components with varying material compositions [45].

In summary, it was found that an important advantage of processes based on multiple materials, that are processed in parallel is that existing extrusion processes only needs to be duplicated and adjusted to the added materials. Complex connections and mixing devices are thus omitted. Therefore, additional materials can be added without increasing the complexity of the extrusion device itself. Furthermore, this approach can be applied to both, filament-based processes and processes which are based on liquid or past like materials.

A disadvantage of such a system is that only sharp interfaces between different materials or material mixtures can be created. Therefore, this approach does not enable the possibility to create gradients between different materials. However, a form of transitions can be created by using specific patterns. Whereas, this approach requires a fine print resolution in order to mimic a gradient. Another disadvantage is that these systems are limited to fixed, predetermined materials. Therefore, it is not possible to create mixtures between the respective materials.

### 4.1.2. Multiple materials processes as a blend of two or more materials

Processes that create a blend of two or more materials (Fig. 2d) are typically characterized by an additional mixing unit. This allows different materials to be blended in specific ratios before extrusion. Different types of mixers that have been reported are discussed at the end of this section. In addition to the mixing unit, these processes typically consist of multiple material containers, feeding devices and a single material outlet. During the printing process, the output material is created by a proportionally mixing of different raw materials, allowing variable gradients to be created between the respective materials.

Two subcategories within the category of processes, based on blending of two or more materials can be defined. First, processes that are based on several material mixtures, where each individual mixture represents specific material properties and can also function on its own (Fig. 2e). During the extrusion process, these materials can be mixed together in any desired ratio, resulting in seamless transitions between the starting materials. The use of this approach has been reported with different material combinations. The Mediated Matter Group at the MIT created graded components based on different polyurethane or silicon compounds [46,47]. Whereas, Craveiro et al. created graded concrete elements based on two different concrete mixtures [48,49].

A variation of blending two or more ready-mixed materials is displayed by Herrmann and Sobek in their research on the automated production of functionally graded concrete components (Fig. 2f). Here, material gradients are generated by a shotcrete process in which two different material mixtures are processed simultaneously with two different spray heads. A volumetric flow control of the respective pumps enables a continuous gradation of the two concrete mixes [50,51]. While the developed spraying technique for graded concrete elements has not yet been implemented in an AM process, current work at the TU Braunschweig on Shotcrete 3D-Printing demonstrates that this type of process can also be used in AM [52].

The second subcategory is characterized by a setup that consists of a main material mixture and a secondary material. The secondary material is usually an additive or filler that can be selectively added (Fig. 2g). The addition of these supplements takes place during the 3D Printing process and thus allow for a variable control of the final material properties. Since the addition of these additives of fillers takes place during the 3D Printing process, the final material properties can be variable controlled throughout the 3D Print.

Several variants of a setup with a main material mixture and a variable additive or filler (Fig. 2g) have been reported. Duballet, Gosselin, and Roux applied this approach to produce concrete elements with graded amounts of added polystyrene beads. A mortar mix was used as the primary material. During the printing process, this material can be continuously modified by adding polystyrene beads in varying proportions. Irrespective of this, further additives are used to adjust the plastic yield value and accelerate the setting of the extruded mortar [53].

Another example of a setup that consists of a main material mixture and a variable secondary material (Fig. 2g) has been reported by Ahmed et al. The research group presented a process in which the additives are transported directly via an airborne transport system to a mixing device, located at the extrusion unit. In this way, fibre particles can be added during printing and thereby change the characteristics of the extruded material. The location of the mixing unit marks the point where the different materials or additives are combined. Positioning it close to the outlet allows quick switching between different properties without having to deal with a long delay [54].

Research on different mixing strategies has been reported in regard to polymer materials as well as in regard to concrete material. Craveiro et al. compared the results of a Y-shape type connector with a dynamic mixing unit in combination with concrete material. Therefore, the cross-section of a 3d printed specimen with two different materials has been investigated. The cross-section shows, that the Y-Shaped type connector leads to insufficient mixing results between the respective materials. In comparison, the use of the dynamic mixing unit led to an overall better mixing result and improved flowability [48].

In addition to this, Oxman, Tsai, and Firstenberg investigated three different mixing strategies (diffusive-, static-, and active-mixing) as part of their research on Variable Property Printing with polymer materials. The diffusive strategy is similar to the Y-shape connector, used by Craveiro et al. The active strategy consists of a set of blades in a reservoir, driven by a small motor. And the static mixing strategy consists of an inline static pipe mixer right before the material outlet. Similar to the results of Cravairo et al. this research shows that either an active or a passive mixing strategy is required to produce an adequate blend between different materials. However, a problem with active or passive mixing is the related delay in switching between the respective materials. This delay, which is mainly influenced by the length of the mixing unit, is reflected in the fact that a certain amount of time elapses before the set material is extruded at the outlet [46].

In summary, an advantage of multi-material strategies that use a blend of two or more materials is that sharp transition between different materials or material properties can be avoided. This allows to distribute possible stresses between the respective materials over a continuous gradient, rather than reducing the connection to a sharp interface. Furthermore, using such a system enabled an almost infinite amount of material mixtures, based on the starting materials. The more materials are used, the greater the variety of possible material mixtures. However, it must be considered that material gradients can only be created along the print path. Therefore, a stepwise gradient between individual print paths may still be present. In case of a point-by-point AM process, a stepwise gradient would be present between the individual points.

A disadvantage of such an approach is the need for an additional mixing unit which adds another level of complexity. In connection with this, new methods must be developed in order to monitor the accuracy and quality of material gradients throughout the 3D Printing process. In addition to this, there is a delay until changes are made in the mixing ratio of the individual materials. However, this delay can be reduced by positioning the mixing unit at the extrusion unit and using the shortest possible mixing unit.

### *4.2. MMAM materials*

In line with the presented multi material processes, suitable materials were investigated and discussed. These materials can be divided into two categories. Firstly, concrete materials whose material properties are modified by additives and fillers. Secondly, polymer materials, in which mixtures of different polymers are usually combined in an AM process.

Moreover, the applied material has to meet a set of specific requirements in order to be processed by AM methods. These requirements differ, in regard to the AM method. If the material is processes in a liquid state, the extruded material has to provide enough initial stability to carry further material layers on top of it without deformation. The curing speed has to be fast enough, that sufficient stability of the 3d printed object can be ensured. At the same time, the material should not harden in the mixing head. A summary of the reviewed projects for MMAM in architecture and construction according to the specific AM process and material is provided in Table 3.

#### *4.2.1. MMAM with concrete type materials*

From varying degrees of strength and corresponding load-bearing capacity, to varying degrees of porosity and thus the related thermal conductivity, to water and moisture resistance. Concrete can have a number of different properties and areas of application, depending on the mixture and respective additives or fillers. These properties can be adjusted by changing the respective composition of the concrete mixture which makes concrete a material with high potential for use in MMAM.

To date, the most common approach in MMAM with concrete is by varying the density of the concrete material. One of the first investigations, that aimed at this was conducted in 2011 by the MIT Mediated Matter group. Referred to as variable density concrete, aluminium powder is used as a foaming agent for concrete. When mixed with unset concrete, the aluminium powder produces a hydrogen gas which causes the concrete mix to foam. By controlling the amount of added aluminium powder, the density of the concrete material can be adjusted. The result is a low-density concrete material which can be used to reduce the overall material weight as well as the material consumption. At the same time, low density concrete elements can also be used to improve the thermal insulation properties of such elements. While this research has not been fully implemented in an AM process, initial steps in form of a material concept have been developed [47].

Following this, Chee et al. reported a variation of this approach in the publication on Locally differentiated concrete by a digitally controlled injection process. Here, the team adopted the approach from the MIT and developed a process which injects a mixture of aluminium powder suspended in water into an unset concrete element. The robotically controlled injection allows for locally altering the material properties throughout the concrete element. However, this process can rather be seen as a refinement step for a conventionally poured concrete element, and not as a MMAM process [61].

A different approach to the use of aluminium powder is based on altering the density of concrete elements by adding low density filler material into the viscous concrete mixture. Here, a wider range of research with different filler materials has been carried out, including polystyrene beads, granulated cork, expanded glass and aerogel. However, not all applied fillers have yet been investigated in full detail.

Moreover, Heinz et al. made an extensive investigation on lightweight concrete, which is based on additives. Therefore, creating a range of potential compound designs including expanded glass, aerogel and expanded pearlite as well as several different foaming agents. The investigation shows that the type of aggregate has a significant influence on the overall performance of the concrete mixture. While insulation performance can be improved by using aerogel aggregates, the use of expanded glass aggregates optimizes the concrete mix in terms of load-bearing capacity while reducing the overall weight of the component. For further investigations with a concrete spaying process (see section 4.1.2, Herman and Sobek) the research group chose a fine-aggregate concrete mix for high-density concrete as one base material and a concrete mixture, based on expanded glass and micro hollow spheres as a second base material. Thereby, providing two different material properties, high-density and low-density concrete for the intended multi-material process [50,55].

Further studies are reported on polystyrene beads [53] and granulated cork [48,49] as filler materials for concrete based AM. Both materials provide low material density, which helps to reduce the overall weight of concrete element, while at the same time improving the insulation properties. The specific amount of filler material can be varied during the 3D Printing process, in order to adjust the material properties in regard to the requirements of the specific component. Mixtures with up to 50% volume of polystyrene beads and 30% volume of granulated cork have been tested through 3D Printed prototypes.

Besides the change in material density, the selective use of fibres represents a second variant of MMAM with concrete. Ahmed et al.

reported the use of fibre materials with a two-stage extrusion process. The selective use of fibres makes it possible to adapt the printed concrete material to local requirements in terms of strength and ductility. The team tested different types of fibres, whereby glass fibres performed best in regard to the specific process (see section 4.1.2, Ahmed et al.). Moreover, an increase in structural strength and ductility through the use of fibres has been proven. However, it was also identified, that the type of fibre and the printing direction have a significant impact on the performance of the fabricated specimen [54].

Finally, colour graded concrete elements are reported as a by-product of some research studies and are mainly used for verification purposes. Such gradients are made by adding colour pigments to one of the premixed mixtures. This method helps to displays the transition between different material mixtures and can be used as a testing method for mixing strategies as reported by Craveiro et al. as well as Heinz, Herrmann, and Sobek [48,55].

#### *4.2.2. MMAM with polymer type materials*

The second type of material reported for use in MMAM are polymer materials. Polymers are common in AM and can be adjusted to a wide range of properties and characteristics. They range from various degrees of porosity and elasticity to a whole range of shades and transparencies. In general, polymers have a low thermal conductivity, a low modulus of elasticity and the performance is strongly temperature dependent. Compared to steel, the thermal expansion of polymers can be ten times higher [62]. However, there are already a variety of polymers developed for AM, that are available on the market.

An early approach on MMAM with polymers has been reported by the MIT Mediated Matter group in 2011. The group tested several polymer materials, including UV curable silicone, polyurethane, as well as different coloured adhesives. For each of these materials, two different compounds were prepared and then extruded in a multi-material setup. Hereby, each compound represents different material properties. In this investigation, a soft and a hard compound was used. During the 3D Printing process, both mixtures are used in parallel, so that different mixtures can be produced between both starting compounds.

In addition, a suitable 3D Printing platform was developed for the deposition and mixing of the selected materials. This enabled the production of first multi-material objects in regard to the respective materials, and thus the delivery of a proof-of-concept. At the same time, however, no specific applications were investigated using this approach. Furthermore, the team points out that future investigations could be carried out with a broader range of material properties by using aggregates, foaming agents, or responsive materials to expand the field of potential applications [46,47].

Another research, which is based on polyurethane material has been reported by Craveiro et al., in 2013. While, also using two different polyurethane compounds, the research differs in terms of processing and deposition strategy. In contrast to the work presented by Oxman et al. the respective material compounds are extruded without being mixed. However, similar to the research by Oxman et al. no specific details of possible future applications have been provided [42].

Also based on polyurethane material, the company Ebalta Kunststoff GmbH, in collaboration with the manufacturer German RepRap, developed an AM process referred to as Liquid Additive Manufacturing (LAM). Unlike the research mentioned above, this approach does not use premixed polyurethane compounds. Instead, the polyurethane compound is made by mixing two components directly before the extrusion. Only after the two components are mixed, does the reaction begin, and thus the curing of the material.

This approach allows faster curing speeds and longer storage of the individual components. In addition, by varying the mixing ratio, the stiffness of the final material can be changed. In this way, components with varying degrees of stiffness can be produced in a single 3D Printing process [63]. While this project is not directly related to architecture and construction. A continuation of the development

**Table 4**
Overview of Potentials of MMAM and current applications in research.

| Potential of MMAM | Benefits | Application area | Used material properties |
|---|---|---|---|
| Functionally graded transitions between different materials | • Reduced stress and strains between different materials | Small scale specimen<br>Structural concrete elements | • Graded change between different degrees of elasticity<br>• Graded change between different degrees of density |
| Adjusting material properties across the volume of an object | • Reduced material consumption<br>• High degree of customization and contextualisation | Small scale objects e. g., chair<br>Structural concrete elements | • Different degrees of elasticity<br>• Different degrees of rigidity<br>• Different degrees of density |
| Eliminating interfaces and enabling part-count reduction across different materials | • Reduction of parts/components<br>• Reduced assembly/construction time<br>• Reduced susceptibility to errors<br>• Reduced amount for coordination between individual trades | Small scale objects e. g., chair<br>Structural concrete elements<br>Partition walls, Modular wall systems | • Different degrees of rigidity<br>• Different degrees of density<br>• Different degrees of stiffness, tensile strength and elasticity as well as translucency and colour<br>• Combining conductive and non-conductive filament |
| 4D Printing, programming material behaviour | • Reduction of parts/components<br>• Reduced assembly/construction time<br>• Reduced susceptibility to errors | Small scale specimen<br>Responsive façade elements | • Combination of material with different coefficients of expansion when exposed to water or humidity |

carried out by Oxman et al. and Craveiro et al. can however, be seen in the Liquid Additive Manufacturing project.

The use of a biopolymer was reported by the Mediated Matter Group at the MIT. More precisely, a Bio-cement composite, containing cellulose, chitosan, cornstarch, pectin and calcium carbonate is used to created 3D Printed structures. Besides the use of a biopolymer, this work is characterized by the possibility to implement a multitude of material properties in a single object. Described as "Parametric Chemistry", the group altered the properties of the extruded material by changing the mixing ratios between all ingredients. Thereby creating variations between different degrees of stiffness, tensile strength and elasticity, while at the same time changing the appearance by influencing the amount of translucency and colour. While previous work mainly focuses on shifting between two different material properties, this research demonstrate that it is also possible to 3D Print objects with a multitude of material properties [58]. In order to test the applicability of this approach, the group designed and manufactured an architectural-scale structure with highly differentiated geometry and with multiple material properties using the Water-based Digital Fabrication (WDF) Platform. Designed as a shell with different mechanical, chemical, and optical properties the research presents a new kind of architectural skins, produced from naturally degradable raw materials [64].

The above projects are all based on polymers that are processed in a liquid state. In contrast, approaches using the FDM process are based on thermoplastic polymers. This requires the material to be heated to a certain temperature so that the material liquefies and can then be extruded through a nozzle. Most commonly, thermoplastics are used in the form of a filament. For use in a multi-material system, multiple thermoplastic filaments can be processed in parallel by using multiple extrusion units and feeders. In this way, each of the extrusion unit can be equipped with a different material and thereby reproduce different material properties.

Correa et al. used thermoplastic polymers to create a composite material that reacts to hygroscopic changes in the environment. This is achieved by combining two different thermoplastics to form a reactive material with high hygroscopic swelling capacity (wood fibre composite) on the one hand and a non-reactive material (nylon, ABS) on the other. Specific patterns developed by the team and implemented using MMAM allowed the material behaviour of the 3D Printed components to be "programmed" according to the humidity of the air [45]. Another use of thermoplastic polymers has been reported by the manufacturer of large-scale 3D Printing machines, Bigrep GmbH. Their project combines a conductive and a non-conductive filament to create a capacity sensor that can be used as a fully integrated electrical switch [70].

The use of Photopolymers in combination with the Material Jetting technology has also been reported by various authors. However, the Material Jetting technology has largely been used for representational models or small-scale use cases and is therefore less in focus of this review [57,59,60,65].

## 5. Potentials of MMAM in architecture and construction

The development of MMAM has the potential to initiate a fundamental shift in the current way buildings are designed and constructed, and components are manufactured. Not only will the prevailing methods be replaced, but rather a new concept of assembly-free construction and manufacturing will be introduced.

The ability to switch between different materials or to change the properties of a material during the 3D Printing process brings numerous benefits. A first glimpse into a possible future with MMAM is provided by several experimental applications reported by different authors. These potential benefits will be discussed in this section.

While the selected projects still require further research, potentials of this technology can already be identified. These include, functionally graded transitions between different materials, adjusting material properties across the volume of an object, Part-Count-Reduction and functional integration across different materials, as well as 4D printing applications. A summary of the potentials in correlation to benefits, application area and material properties is provided in Table 4.

### 5.1. *Functionally graded transitions*

Materials with changing composition or structure across the volume of the material are described as the Functionally Graded Materials [66]. Functionally Graded Materials first appeared as a novel type of materials exposed to high heat loads and thereby to a large amount of thermal stress. Therefore, a combination of a ceramic and a metallic material with a gradual transition between both has been developed in order to endure a maximum temperature of 2000K and a temperature difference of 1000 K [67].

Oxman et al. adapted this idea in combination with AM for a wider range of materials, including variable density concrete and polymers with varying degrees of stiffness. This not only introduces a new way of joining different materials through gradual transitions, but also a way that can reduce stresses and strains between the respective materials [47]. Further examples of functionally graded transitions with variable density concrete can be found in the research conducted by Duballet et al. Craveiro et al., as well as Herrmann and Sobek.

Using MMAM has the potential to create Functionally Graded Materials. However, graded transitions are usually limited by the process characteristics itself, namely the line by line approach. Here, a gradual transition is only possible in the direction of the 3D Printing path. If several paths are placed next to each other, stepwise gradations can occur. Furthermore, this review also includes processes which are not able to create gradual transition between different materials. Thus, relay on sharp interfaces between the used materials.

### 5.2. *Adjusting the material properties across the volume of an object*

An example of this benefit are objects with optimized material properties according to specific criteria or environmental conditions. This capability ultimately leads to building elements and, by extension, to entire buildings that exhibit a higher degree of customization and contextualisation.

First applications of this concept can be found in smaller objects such as the Gemini chaise lounge chair by Neri Oxman or the Durotaxis chair by Synthesis Design + Architecture. Both examples take advantage of the ability to define material properties across the entire object, demonstrating the ability to create objects with a high degree of material differentiation and customization. Oxman uses different degrees of elasticity on the inside of a chair to achieve different levels of sound absorption [57]. The Durotaxis chair, on the other hand, consists of a gradual change in stiffness. In this way, the material properties are adapted to ergonomic and structural requirements [59]. It must be made clear, however, that both examples are not specific applications in the field of architecture and construction. Nevertheless, these examples are indicative and show how and with which functions an application in architecture and construction would be possible.

At the same time, section 4.1 and 4.2 shows which materials and which processes might be suitable to realize similar functions in a context strongly related to architecture and construction. MMAM with polymers could be particularly suitable here. Processes such as large-scale FDM 3D Printing or extrusion-based AM with liquid polymers already show that it is possible to combine different material properties, including stiffness and elasticity. Yet there is a lack of examples that build on such processes to develop concrete applications.

An example more closely related to the field of architecture and construction was described in the publication Functionally Graded Rapid Prototyping by Neri Oxman. This publication put forward the hypothesis that "density gradients in structural building components made of concrete may increase the strength of a structural component while reducing material waste." [47]. Thus, material can be used more efficiently by optimizing the bending-stiffness relative to the weight of a concrete component. Further development of this concept was reported by Duballet et al. Craveiro et al. as well as Ahmed et al. These studies investigated different material compositions and processing concepts to altering specific performance parameters of concrete elements, including material weight, insulation value, and ductility.

In line with that, Herrmann and Sobek investigate the potential of functionally graded concrete in more detail by examining the use case of concrete element ceilings. The aim of this research was to investigate the potential of functionally graded concrete materials in order to reduce the overall weight and thus material consumption of such components. This work resulted in a total reduction of the overall weight of such components of up to 43%, when combined with steel reinforcement and up to 59% in combination with textile reinforcement [56].

### *5.3. Eliminating interfaces and enabling part count reduction across different materials*

Another potential of MMAM is that specific interfaces between different materials can be eliminated and subsequent assembly processes become redundant. AM already offers the possibility to reduce the total number of components by creating more complex geometries. However, MMAM extends this capability by also allowing the combination of different materials. Furthermore, this could potentially lead to simplified designs, reducing overall construction time and the potential to errors. Fewer workers are needed for construction and the coordination effort between the various trades could be reduced.

How this can be implemented can be seen in the above example of the Durotaxis chair. The combination of different material properties makes it possible to manufacture a chair without any assembly, able to function structurally as well as providing softness and comfort [59]. However, similar to section 5.2, there is a gap between this example and an application in architecture and construction. Nevertheless, a connection to already identifiable approaches can also be made (See 5.2).

Furthermore, an example that not only demonstrates the potential to simplify assembly and reduce the overall number of parts, but is also located in the field of architecture and construction, is shown by Duro-Royo et al. This project presents a highly differentiated skin-like structures that combines mechanical performance and varying transparencies and appearance on its surface. By combining several material compounds, the research group was able to incorporate a variety of properties, including stiffness, tensile strength, elasticity as well as translucency and colour. Ultimately, resulting in a single envelop that combines structural and visual functions at the same time. Therefore, a process for multiple materials that are processed in parallel or as discrete entities was developed in combination with a large range of biopolymers compounds [64].

An application example based on the FDM process is provided by the 3D Printer manufacturer BigRep. They developed a touch-sensitive sensor that can be integrated into a modular wall system via 3D Printing [70]. The sensor itself is based on the combination of a conductive filament with a non-conductive filament. This not only demonstrates that components such as the touch-sensitive sensor can be manufactured, but also that they can be integrated into larger components such as a modular wall using 3D Printing. This not only eliminates the need to acquire such parts additionally but also to assemble them (We 3D Printed a Sensor with Conductive Materials, 2018).

The potential to eliminate interfaces and reduce the overall amount of individual parts is also evident in multi-material applications with concrete. By varying the material density in concrete elements, the load-bearing capacity of concrete can be extended with additional insulating properties. Ideally, an additional insulating layer can thus be omitted. Several examples of the implementation of this approach have been presented. Both Craveiro et al. and Duballet et al. use a modified version of 3D Concrete Printing in which the material density is selectively reduced by an additional filler [48,53]). Herrmann and Sobek, on the other hand, achieve the combination of different material densities using a shotcrete process. Similarly, an additional filler is used to reduce the material density [50].

### *5.4. 4D printing, programming material behaviour*

4D Printing presents a further potential of multi-material additive manufacturing. Also described as "programming" material behaviour, the material is designed and manufactured in such a way, that the material itself is able to change form or function when actuated. Therefore, completely omitting further external devices and electromechanically systems. Ultimately this leads to a reduction of components, which are otherwise needed in order to provide this specific function. Assembly time, cost, and susceptibility to errors could be reduced as well (Skylar, 2014).

The Self-Assembly Lab at the MIT reported a set of projects which demonstrate the potential of 4D Printing.

Therefore, the group used the material jetting process and combined a rigid plastic material with a material that expands when exposed to water. When both materials are combined in a specific pattern, the interaction of expansion and non-expansion can lead to a defined transformation or change of form, when actuated with water.

Moreover, this approach can be used for various different applications including, self-transforming functional structures and self-adapting building material that adapt upon to environmental changes (Skylar, 2014).

Even though the examples generated in this work clearly show the functionality, a transfer of this to construction practice is not yet clearly evident.

A further example is the work of Correra et al. on 3D Printed hygroscopic materials that react to moisture similarly as wood veneer. Two materials with different elongations at high humidity were combined into a single composite. Similar to the research at the Self-Assembly Lab, the use of specific design patterns created by combining the two materials, results in a defined shape change when activated. For this, an FDM process with multiple extrusion units was used, equipped with the appropriate filaments. Furthermore, Correra et al. applied this concept to a “Multi-Kinematic-State climate-responsive aperture” that allows shape change in response to environmental changes without the need for other external devices [45].

## 6. Conclusions and future directions

The concept of Multi-Material Additive Manufacturing is beginning to gain traction in the field of architecture and construction. Although, only limited research results are currently available, initial approaches and first prototype applications have been reported by various authors. In line with the rapid development of Additive Manufacturing in this sector, further developments and new concepts for Multi-Material Additive Manufacturing, adapted to the requirements of this specific industry are therefore to be expected.

The main focus when it comes to the processing of multiple materials by means of Additive Manufacturing is on material extrusion. This is because this type of process can be extended to multiple materials relatively easy and is already widely used in large-scale AM with single materials. Different concepts for the use of multiple materials in extrusion based additive manufacturing were identified in the reviewed research projects. These were categorized into two different types. First, multiple materials processed in parallel and as discrete entities and second, multiple materials processed as a blend of two or more materials. In addition to this, the respective advantages and disadvantages of both types were discussed.

Multiple materials processed in parallel, as discrete entities:

Advantages:

- Can be extended with similar extrusion units
- Can be applied to both, filament-based extrusion processes and processes that are based on a liquid or paste like material

Disadvantages:

- Only sharp interfaces between the different materials can be created
- Only fixed, predetermined material properties can be created

Multiple materials processed as a blend of two or more materials:

Advantages:

- Graded transition between different materials or material properties are possible
- Different mixing ratios can be set between the starting materials, and thus enable a wide range of possible material mixtures.

Disadvantages:

- The need for an additional mixing unit, which adds another level of complexity.
- Through the additional mixing unit, a delay occurs when changing the material composition

Moreover, the individual concepts lead to different types of material transitions between the starting materials with corresponding advantages and disadvantages.

- While multiple materials processed in parallel are restricted to the extent that only sharp interfaces between the respective materials can be created.
- The approach of multiple materials processed as a blend of two or more materials enables the creation of gradual material transitions along the printing path.

While sharp interfaces lead to defined material properties at every point of the additive manufactured object, the abrupt change between two materials can lead to stresses being caused between the materials due to different material behaviour. Consequently, these can lead to delamination of the individual materials. At the same time, is must be ensured that the combined materials exhibit good adhesion.

In contrast, graded transitions allow for a better distribution of stresses between different materials. However, due to the process characteristics of creating 3D Printed paths, fully graded transitions can only be created along the printing path. Abrupt changes in material composition of properties can still occur between the 3D Printed paths or the respective layers of the Object.

In terms of material, research has been reported on concrete and polymers. Similar to large-scale 3D Printing with homogeneous materials, a strong focus on concrete materials and thereby structural components was identified. Here, most projects focus on changing the density of the material by using lightweight fillers or foaming agents. In addition, research on increasing the ductility of concrete elements by adding fibre materials has also been reported. However, more research is needed to fully introduce this technology into large-scale Additive Manufacturing. While concrete printing apertures are already commercially available, the ability use multiple materials in a single 3D Print has yet to be fully implemented at this scale.

In contrast, research on polymers, and thereby non-structural components is less in focus. However, specific applications using the FDM process with multiple filaments as well as the extrusion of biopolymers have been reported. This involves combining material properties such as conductivity and non-conductivity, different degrees of material stiffness, different colours and transparencies, and different degrees of material elongation.

At the same time, research into polymers such as silicon or polyurethane was also reported. Although the state of research on these polymers is not yet sufficiently advanced to derive future applications, further research can be expected. Compared to FDM, methods for processing liquid polymers in an extrusion-based AM process are less common. However, the use of such materials may increase in the near future through processes such as LAM.

Overall, it has been noted that the approaches taken to date focus either on a specific starting material, commonly concrete, which has been altered through additives, or a specific process that can be extended with the same type of material such as thermoplastics.

Finally, initial projects and proof-of-concept models aim to mitigate the general challenges of the industry, such as high material consumption, limited adaptability of components to environmental changes and structural requirements, and an overload of complexity of the prevailing assembly and construction processes. From these projects, the potentials of creating functionally graded transitions, adjusting the material properties across the volume of an object, eliminating interfaces and enabling part-count reduction across different materials, and 4D Printing – programming material behaviour were identified and discussed using the respective examples. These potentials highlight opportunities for MMAM in the architecture and construction industry that can be further developed and transferred to other use cases. However, there is currently little research on the effectiveness of these potentials and their use in practice.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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