POLITECNICO DI BARI

D.R.S.A.T.E.

08

2025

Doctorate in Risk And Environmental, Territorial And Building Development

Coordinator: Prof. Vito Iacobellis

XXXVII CYCLE
Curriculum: ICAR/10

DICATECh
Department of Civil, Environmental, Building Engineering and Chemistry

Stelladriana Volpe

An integrated methodology for supporting the design of 3D-printed building components

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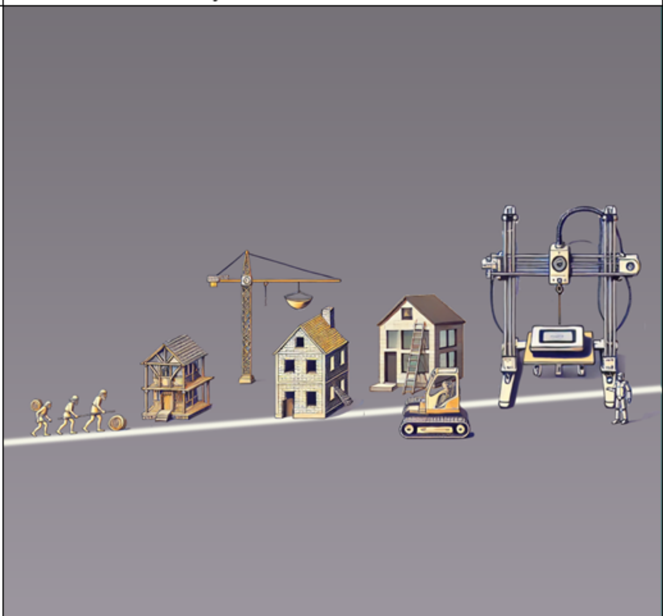

Politecnico di Bari

LIBERATORIA PER L'ARCHIVIAZIONE DELLA TESI DI DOTTORATO

Al Magnifico Rettore
del Politecnico di Bari

La sottoscritta Stelladriana Volpe nata a Bari il 10/08/1996
residente a Bari in via Gentile 97 e-mail stelladriana.volpe@poliba.it
iscritta al 3° anno di Corso di Dottorato di Ricerca in Rischio, Sviluppo Ambientale, Territoriale Ed Edilizio ciclo 37° ed essendo stata ammessa a sostenere l'esame finale con la prevista discussione della tesi dal titolo:
An integrated methodology for supporting the design of 3D-printed building components

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“Animum debes mutare, non caelum”

Il luogo non basta, e per ritrovarsi
“non occorre che tu sia altrove, ma che tu sia un altro”.

Seneca, Epistole a Lucilio

EXTENDED ABSTRACT *(eng)*

To date, the construction industry is globally among the most impactful on the environment. A look into the past may lead to questioning about how housing systems have been transformed and how to cope with current critical issues. A common factor in past architectural styles for each location has always been the adaptation to the climate and the natural environment. To address the heat, cold, and winds of the site where they were to be built, building types were adapted with specific shapes and materials, often sourced locally. As a result, the transformation of constructions over the centuries has given a varied architectural landscape, unique to each region of the world.

This trend was reversed starting from the Second Industrial Revolution when standardized construction techniques replaced traditional and local methods. The use of reinforced concrete spread across all latitudes, influencing architectural forms, which were no longer adapted to the local climate. To meet the thermo-hygrometric requirements of indoor environments, increasingly widespread thermal conditioning systems were used. This made it possible for the same building to be constructed anywhere in the world. The consequences of this approach are among the causes of the current significant environmental impact of the construction sector. Indeed, the reduced use of local materials, increased consumption of raw materials, increased transportation of construction elements, and higher energy consumption all contribute to increased emissions. Another aspect that has been irreversibly neglected in the last century is the variety of architectural forms and their corresponding adaptation to the surrounding environment.

During recent decades, the technological progress of the construction industry has been very slow compared to other industrial sectors, which have increased productivity and efficiency by adopting innovative technologies. 3D printing is a production

technology already established in other industrial sectors, and the interest in using such technology for construction has rapidly grown, proving to be one of the most promising technologies to innovate the construction sector. Its potential includes cost reduction, reduced energy consumption, lower material waste, automation of construction processes (thereby reducing risks for workers and the chance of errors), increased productivity, and greater efficiency. Moreover, 3D printing technology offers a greater degree of freedom in architectural forms, allowing curved and three-dimensional shapes to be realized more easily compared to traditional technologies. This architectural freedom could provide a solution to the search for a sustainable construction approach, as it would allow for a renewed connection between architectural forms and the surrounding environment.

The primary goal of this thesis is to explore the possibilities that 3D printing offers to the construction industry. Specifically, by studying the evolution of 3D printing in construction both from a market and scientific innovation perspective, the current limitations to the widespread applicability of 3D printing for building construction have been highlighted. For 3D printing to become an established technology in construction, the printed products must be competitive in terms of performance within the existing market. To overcome some of these limitations, this study proposes a methodological approach to support the design of building components, based on the parameterization of digital models and the iterative analysis of their performance. This allows for the creation of adaptable building elements suitable for different boundary conditions and prefabricated using 3D printing technology. The proposed methodology follows a four-phase iterative process: I. design development and parametric modelling; II. definition of performance criteria and boundary conditions; III. performance simulation and parameter identification; IV. production with 3D printing. In particular, the first three phases are repeated until the model's parameters are refined to achieve optimal performance under the specified conditions.

The methodological approach has been employed in various applications and related case studies that specifically implement the basic methodology regarding aspects of thermal performance, recycling of raw materials, sustainability, and the environmental impact of construction processes. Among the various performance characteristics (acoustic, structural, environmental impact, lifecycle, etc.) that a building component must meet, the case studies focus on fulfilling thermal performance requirements. This characteristic is crucial for the effective use of the designed building products. Additionally, the applications aim to demonstrate the correlation that can occur between geometry and the thermal path that affects the overall transmittance of an envelope, and thus the tangible advantage that can result from the use of 3D printing, which allows for a high degree of geometric freedom.

A common feature of the developed case studies is the use of 3D printing as a technology for the prefabrication of building components, rather than for the large-scale on-site production of buildings, providing examples of this use.

The applications aim to increasingly automate the parameter efficiency process based on boundary conditions. Starting from a manual iterative method, which involves modifying parameters and then repeating simulations, a workflow was developed to allow for automatic simulations as parameters vary until the goal is reached.

Finally, the approach was adopted for experimental work focused on the development and prototyping of an envelope system made of prefabricated cementitious elements using 3D printing. A preliminary phase focused on modifying a cementitious mix to improve its performance according to printing requirements. Additionally, 3D printing tests were conducted to adapt and optimize the initial geometry to meet the requirements of the employed printer. Ultimately, a full-scale prototype element was produced.

keywords

3D construction printing, bibliometric analysis, cluster analysis, parametrization, iterative thermal analysis, cementitious mixtures, envelope components, architectural engineering

***EXTENDED ABSTRACT** (ita)*

L'industria delle costruzioni ad oggi è globalmente fra le più impattanti sull'ambiente. Uno sguardo al passato può farci interrogare su come si siano trasformati i sistemi abitativi e su come sopperire alle criticità attuali. Un fattore comune nelle architetture del passato è sempre stato ad ogni latitudine l'adattamento al clima e al contesto naturale. Per far fronte al caldo, al freddo, ai venti del sito in cui sarebbero sorte, le tipologie edilizie venivano adattate con specifiche forme e materiali il più delle volte reperiti localmente. È così che la trasformazione delle costruzioni attraverso i secoli ci ha restituito un panorama architettonico vario e distinto per ogni area della terra.

Questa tendenza è stata invertita a partire dalla seconda rivoluzione industriale quando la standardizzazione di tecniche costruttive ha preso il posto di metodi tradizionali e locali. L'uso del calcestruzzo armato si è diffuso ad ogni latitudine condizionando le forme architettoniche non più adattate ai contesti climatici. Per sopperire alle esigenze di natura termo-igrometrica degli ambienti interni si è fatto quindi ricorso agli impianti di condizionamento termico sempre più diffusi. Ciò ha reso plausibile che lo stesso edificio potesse essere costruito in qualunque parte del globo. Le conseguenze di questa attitudine possono essere annoverate fra le cause dell'attuale grande impatto del settore delle costruzioni sull'ambiente. Infatti, il minore uso di materiali locali; il maggiore consumo di materie prime; l'aumento dei trasporti di elementi costruttivi; il maggiore consumo energetico concorrono all'incremento delle emissioni. Un ulteriore aspetto irrimediabilmente trascurato nell'ultimo secolo è stato la varietà delle forme architettoniche e il corrispondente adattamento all'ambiente circostante.

Negli ultimi decenni il progresso tecnologico dell'industria delle costruzioni è stato molto lento se comparato ad altri settori industriali che hanno aumentato la propria produttività ed efficienza adottando tecnologie innovative. La stampa 3D è una tecnologia produttiva, già affermata in altri settori industriali, il cui interesse si è rapidamente diffuso per l'impiego nelle costruzioni rivelandosi una delle tecnologie più promettenti per innovare il settore. Le potenzialità riguardano la riduzione di costi, la riduzione dei consumi energetici, la riduzione di materiali di scarto, l'automatizzazione dei processi costruttivi riducendo i rischi per i lavoratori e le possibilità di errore, l'aumento della produttività e l'aumento dell'efficienza. Inoltre, la tecnologia di stampa 3D offre un maggiore grado di libertà per le forme architettoniche ossia forme curve e variabili nelle tre dimensioni possono essere realizzate facilmente rispetto a quanto permettano tecnologie tradizionali. Questa libertà architettonica potrebbe fornire una risposta alla ricerca di un approccio sostenibile alle costruzioni, in quanto consentirebbe di ritrovare un legame tra forme architettoniche e ambiente circostante.

Lo scopo principale del presente lavoro di tesi è esplorare le possibilità che la stampa 3D offre all'industria delle costruzioni. In particolare, studiando l'evoluzione della stampa 3D per l'edilizia sia dal punto di vista del mercato che dell'innovazione scientifica, sono stati evidenziati gli attuali limiti all'applicabilità diffusa della tecnologia di stampa 3D per la costruzione di edifici. Affinché la stampa 3D delle costruzioni diventi una tecnologia affermata infatti è necessario che i prodotti edilizi stampati risultino concorrenziali nel mercato esistente dal punto di vista delle performance. Per superare alcuni di questi limiti, la corrente trattazione propone un approccio metodologico di supporto alla progettazione di componenti edilizi basato sulla parametrizzazione di modelli digitali e sull'analisi iterativa delle prestazioni degli stessi per ottenere elementi di involucro adattabili a diverse condizioni al contorno e prefabbricabili con la tecnologia di stampa 3D. La metodologia proposta segue un processo iterativo di quattro fasi: I. sviluppo del design e modellazione parametrica; II. definizione dei criteri prestazionali e delle condizioni al contorno; III. simulazione delle prestazioni e identificazione dei parametri; IV. produzione con stampa 3D. In particolare, le prime tre fasi vengono ripetute fino a quando i parametri del modello vengono perfezionati per ottenere prestazioni ottimali nelle condizioni al contorno specificate.

L'approccio metodologico è stato impiegato in diverse applicazioni e relativi casi studio che nello specifico implementano la metodologia di base riguardo gli aspetti

delle performance termiche, del riciclo di materiali come materie prime, della sostenibilità e degli impatti sull'ambiente dei processi costruttivi. Tra le diverse caratteristiche prestazionali (acustiche, strutturali, di impatto ambientale, di ciclo di vita, ecc.) che un componente edilizio deve soddisfare, i casi di studio in esame si concentrano sul soddisfacimento delle prestazioni termiche. Questa caratteristica è fondamentale per l'utilizzo effettivo dei prodotti edilizi progettati. Inoltre, le applicazioni hanno lo scopo di dimostrare la correlazione che può verificarsi tra la geometria e il percorso termico che influisce sulla trasmittanza totale di un involucro e quindi il vantaggio concreto che può derivare dall'uso della stampa 3D, che consente un elevato grado di libertà geometrica.

Un aspetto comune dei casi di studio sviluppati riguarda l'uso della stampa 3D come tecnologia per la prefabbricazione di componenti edilizi piuttosto che per la produzione in loco di edifici su larga scala, fornendo esempi di impiego.

Le applicazioni affrontate mirano a rendere sempre più automatizzato il processo di ottimizzazione dei parametri, in funzione delle condizioni al contorno. Partendo da un metodo iterativo manuale, che consiste nel modificare i parametri e poi ripetere le simulazioni, è stato sviluppato un flusso di lavoro che consente di effettuare simulazioni automatiche al variare dei parametri fino al raggiungimento dell'obiettivo.

Infine, l'approccio è stato adottato per un lavoro sperimentale di sviluppo e prototipazione di un sistema di involucro costituito da elementi cementizi prefabbricabili con stampa 3D. Una fase preliminare si è concentrata sulla modifica di una miscela cementizia per migliorarne le prestazioni in base ai requisiti di stampa. Inoltre, sono stati condotti test di stampa 3D per adattare la geometria iniziale e ottimizzarla rispetto ai requisiti della stampante impiegata. Infine, è stato realizzato il prototipo di un elemento in scala reale.

keywords

Stampa 3D nelle costruzioni, analisi bibliometrica, analisi con cluster, parametrizzazione, analisi termiche iterative, miscela cementizia, componenti d'involucro, ingegneria edile.

INDEX

1. INTRODUCTION

1.1. Background

To date, the construction sector is responsible for about 40% of total CO_2 emissions [1], but humans have been inhabiting this planet and building houses on it for probably 10,000 years. Therefore, to understand and solve one of the most pressing problems of our present, we might ask ourselves how housing systems have been transformed. A common factor in architecture around the world has undoubtedly been the adaptation to climate and the natural context. Thus, to cope with excessive heat, cold, wind, etc., building types were adapted by their shapes and the materials they were composed of. Moreover, materials often had to be sourced locally.

Since the Second Industrial Revolution, construction techniques have become standardized, replacing traditional and local methods. Specifically, the use of reinforced concrete has been spread to every latitude influencing architectural forms. Therefore, thermal conditioning systems became necessary to meet indoor environments' thermal-hygrometric needs. That has made it possible to build the same building anywhere in the world. Of course, the consequences of all the above have caused the increased construction industry's impact on the environment. Major consequences include: less use of local materials; increased transport of raw materials; greater consumption of raw materials; higher energy consumption and consequent environmental impact. Reconnecting to what was introduced earlier, another important consequence is the loss of the variety of architectural forms and their adaptability to local contexts, aspects that have been greatly neglected in the last century.

Since then, technological progress in the construction industry has been very slow compared to many other industries that have exponentially increased productivity and efficiency using innovative technologies. The application of new production technologies and automated systems to the construction industry has the potential to reduce costs, reduce energy consumption, reduce waste materials, automate hazardous processing for workers, minimize the possibility of error, increase productivity and increase efficiency. In addition, 3D printing technologies provide a greater degree of freedom for architectural forms. In fact, curved and variable shapes in three dimensions can be produced more easily than in the past. This new freedom could be the response to the research of a sustainable approach to building systems as there could be a return to a bond between architectural forms and adaptation to the surrounding environment.

In recent years, 3D printing, already widespread in production systems of other industrial sectors, has also gained a foothold in the construction industry. The large-scale 3D concrete printing technology can no longer be regarded as experimental since its use for mass production is increasingly. Nowadays, a large number of companies are building houses printed directly in situ, while the use of 3D printing for precast of building components constitutes a research field of broad interest.

One of the first extrusion machines for construction has been patented by William E. Urschel. In the late 1930s in Valparaiso, Indiana, a film was recorded showing a machine capable of printing strip material by pouring bulk material that is compacted by moving elements. The machine could use rammed earth also stabilized with cement [2,3].

Robotic systems for construction have been developed since the 1960s, but the introduction of innovative technologies into the construction industry has proceeded very slowly since then.

Contour Crafting technology for cementitious materials and concrete, invented by Dr. Behrokh Khoshnevis of the University of Southern California, was introduced in 1996. It was presented at the 19th International Symposium on Automation and Robotics in Construction in 2002. The technology is based on extruding the outline of a vertical formwork made of cementitious material that could then be completed with a concrete casting inside it. The main advantage is that it precisely constitutes a disposable formwork made of cementitious material without the need to use, for example, wooden formwork, which is a waste material in the reinforced concrete production process. In addition, side trowels are attached to the press head so that the surface is smooth. Once the formwork is completed, concrete is poured in 13 cm layers at one-hour intervals so that the lateral pressure exerted by the flowing concrete on the walls is limited, allowing it to cure gradually. The adhesion between layers depends on the type of binder, the size of aggregates and the time interval elapsed between depositions, these parameters must be controlled to not create discontinuity surfaces at the interface between layers. Structural reinforcing elements or plant piping can be incorporated. This method has since been replicated in other technologies with some variations. In fact, currently, material extrusion, which is the additive manufacturing process in which material is selectively dispensed through a nozzle or orifice, is the type with the most applications in construction [4,5].

Another milestone in the development of 3D construction printing was the patenting of D-Shape technology in 2005. This technology is based on selective binding also known as binder jetting i.e., the additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials. First, a layer of loose granular material smoothed by a roller is spread over which a nozzle draws by pouring binder. The print head selectively pours the binder, e.g. water, following the path dictated by the geometry of the layer corresponding to the model section of the object. The binder mutually binds the particles in the poured area while leaving the material in the other areas loose. Depending on the printer, the frame raises or lowers the platform by the height of the layer. A new layer of material is then laid down and the procedure is repeated. When layering is complete, the container and all of the unbound material is removed, and then the printed object emerges. The unbound material removed can then be reused [6].

From this time on large-scale 3D printing technologies, namely the use of 3D printing for building scale products, began to spread. This widened interest in 3D printing for construction soon reached a global scale. In particular, the most common 3D printing technology is the extrusion of cementitious materials, an additive manufacturing technology defined as the process in which material is selectively dispensed through a nozzle [7]. The production starts with a 3D model sliced into multiple cross-sections and translate into a G-code, the machine language that commands the printer. Then the object can be built layer by layer with a controlled dispensing of cementitious material [8–10].

The cementitious mixtures used in 3D construction printing technology can be of different types. To date, both more common mortars based on ordinary cement and aggregates of different sizes and cementitious mixtures, with innovative types of cement and additives that modify their performance, have been used. The employment of additives can manipulate the printability and the flowability of mixtures, the setting time, or the mechanical properties of both wet and cured concrete.

3D concrete printing technology combines the innovation of the use of 3D printing in the construction sector with one of the most used materials in the building construction industry. This union allows to overcome some of the disadvantages of using concrete such as the production of waste in the production process. The 3D printing of concrete building components does not require formworks and enables the creation of complex geometries with extreme freedom and without additional cost.

The integration of digital fabrication and prefabrication is a prominent topic in contemporary research [11]. At ETH Zürich, prefabricated concrete slabs have been developed using concrete 3D printing, while at TU Gratz, 3D printed formwork has been utilized for similar purposes [12,13]. Additionally, Anton et al. have explored 3D concrete printing prefabrication platforms for custom columns [14]. Generally, additive manufacturing for building envelope elements offers significant geometrical freedom and adaptability in design [15]. These capabilities are particularly useful for studying free-form shapes and optimizing component designs [16].

Some projects exploit the possibility of geometrically characterising individual wall elements in order to create self-supporting structures or textured wall surfaces. The interaction of components of self-supporting systems depends on the precision of production of the single elements. The surface shape of the masonry can be varied to satisfy ventilation, shading, or design requirements [17]. Other studies investigate the interlocking system of individual bricks taking advantage of the design freedom. Many projects are masonry-type wall constructions. Thanks to geometrical freedom, the construction of vaulted structures whose individual parts can be customised are also possible. Moreover, some of these systems can be made up of self-supporting components [18].

The 3D printing technology allows also the design of infill patterns that would be difficult to realize with other technologies. At the same time the degree of density and complexity of the fill geometry depends on the accuracy of the printer. The design freedom of infill patterns has enabled the study of internal structures optimized in terms of compressive strength, thermal conductivity and material consumption.

Nowadays, many companies have started printing their own 3D printed buildings worldwide. On the other hand, future directions will certainly involve investigating the sustainability of these works and investigating the performances that can be achieved by the printed building products.

1.2. Literature gaps

The preceding paragraph has introduced an overview of the thesis' background. Overall, many research topics have been addressed, each highlighting research paths not yet explored but with potential for the establishment of 3D printing in the construction industry. The literature gaps that that led to the development of the proposed research are highlighted below.

- *Precast of building components*
  As mentioned, the different 3D construction printing systems developed are centered on large-scale in situ printing. However, 3D printing technology also has enormous potential to precast and customize building components easily. The potential of additive printing for the prefabrication of smaller components has demonstrated the need to implement the performance of this technology to get to the production of, for example, envelope components. Implementing the quality and print scale of cementitious objects involves the need to evaluate tolerances even considering quick changes of geometric parameters of the digital model to achieve the desired print.
- *Correlation between cementitious mixtures and printing*
  As will be detailed in later chapters, the majority of 3D printed buildings are based on the use of cementitious materials. The investigation of printable cement mixtures although extensive in the existing literature

often depends strictly on geometric factors. Hence, the correlation between specific composition and printing parameters is of significance.

- *Performance and environmental impact evaluation*
  3D construction printing applications realized to date aim to demonstrate the efficiency of the technology mainly from the point of view of production speed and versatility. For 3D construction printing to become an established construction method, building products must also be competitive at the construction market level from the point of view of performance and environmental impact.

1.3. Thesis aim and research questions

The main purpose of the thesis is to explore the possibilities that 3D printing offers to the construction industry. In particular, by studying the evolution of 3D construction printing from both market and scientific innovation perspectives, the current limitations to the widespread applicability of 3D printing technology for building construction were evinced. To overcome some of these limitations, this thesis proposes a methodological approach based on parametric design supported by an iterative thermal performance analysis to obtain building envelope components adaptable to different boundary conditions and prefabricated by 3D printing technology.

The above-mentioned objectives have been pursued by answering the following research questions.

Research questions:

RQ1 How does the additive manufacturing technology work and what types exist?

RQ2 How can be compared the evolution of 3D construction printing in both scientific research and construction market?

RQ3 Which are the milestones of the development of 3D construction printing technology in construction companies and scientific research?

RQ4 How can 3D printed building components meet multi-objective performance?

RQ5 How can 3D printing be employed for the prefabrication of envelope components?

RQ6 What is the actual thermal performance of molded building components?

RQ7 What are the environmental impacts of the entire life cycle of printed components?

RQ8 How can cement mixtures be optimized according to printing requirements?

RQ9 How can geometry be optimized according to printing requirements?

1.4. Structure of the thesis

The development process of the present research can be summarized as follows. The work has been developed by conducting an in-depth investigation and collection of data on the existing technologies and literature on 3D construction printing. Out of this preliminary overview, research topics with open questions have been revealed. Some considerations about how the establishment of this technology can be supported at the market level have been elaborated. Then the research questions that formed the core of the proposed methodological approach were formulated. The methodology for supporting the project of 3D printable envelope was then employed to different applications and relative case studies refining the process. Finally, the approach has been used for the prototyping of a 3D printed envelope component. The preset dissertation is divided into six chapters. For each chapter, an introduction is provided in order to contextualize the research questions addressed. Fig. 1 organizes the structure of the thesis and clarifies the relationship between each chapter and the related research questions.

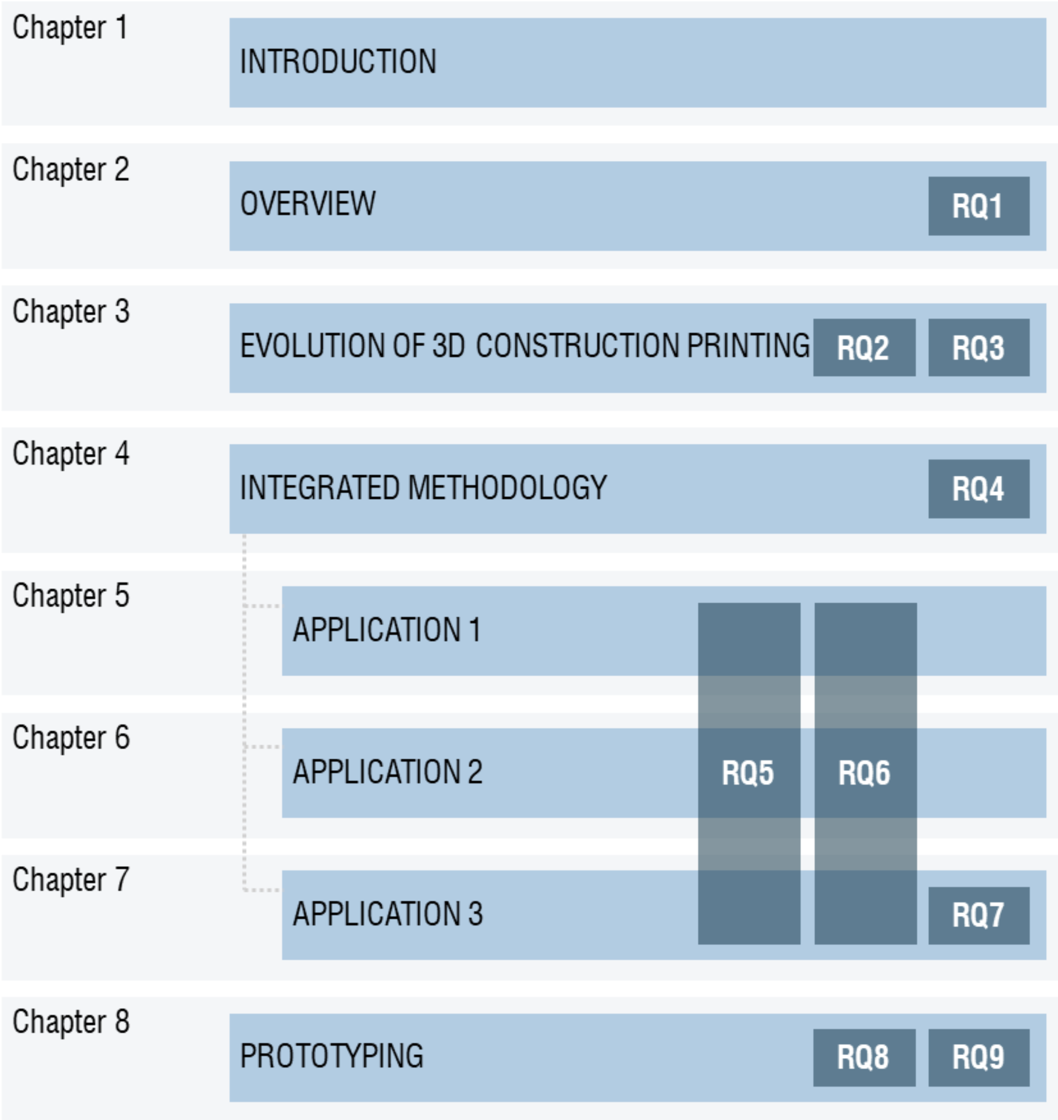


Fig. 1 - Structure of the thesis, outlining the research questions addressed in each chapter.

This **first chapter** aims to provide the background of the research, highlight the literature gaps considered, and explain the research questions supporting the work.

The **second chapter** overviews additive manufacturing technologies focusing on the different types of materials and related applications answering **RQ1**. The principal aim is to introduce the reader to the technological context of 3D construction printing.

In addition, the main technologies and the most widely used materials in this field are outlined.

The **third chapter** delves into the latest advancements in 3D construction printing, highlighting the contrasts and distinctions between academic research and industry progress answering **RQ2**. This comparison offers a thorough overview of how academia and the professional sector function differently, pinpointing both gaps and opportunities. Moreover, a roadmap and future directions for the development of 3D printing technology in construction companies and research have been outlined to answer **RQ3**.

The **fourth chapter** presents the developed methodological approach. In particular, the cornerstones of the method are parametrization and iterative analysis. The development of this methodology aims at increasing the performance of the printable element to be designed in several aspects. Increased performance can make building components competitive at the market level. So, the focus of the developed methodology on element design is intended to be a possible response to **RQ4**, which is to focus on the design and performance of the printed product in order to make 3D printing technology widespread as a building production technology.

The subsequent three chapters present the different applications and subsequent case studies through which the mentioned methodological approach has been developed. Applications tackled aim to make the process of optimizing parameters, depending on boundary conditions, increasingly automated. Starting from a manual iterative method, that consisted of changing parameters and then repeating the simulations, a workflow was developed that allows for automatic simulations as parameters change until the target is reached. A common aspect of the case studies developed concerns the use of 3D printing as a technology for prefabrication of building components rather than on-site production of large-scale buildings providing examples of employment (**RQ5**). As the thermal performance aspect of printed building elements has not yet been sufficiently investigated, it has become one of the recurring research questions (**RQ6**) in the applications of the developed methodology. Among the different performance characteristics (acoustic, structural, environmental impact, life cycle, etc.)

that a building component must expect, the case studies under investigation focus on the fulfilment of thermal performance. This characteristic, as introduced, is of fundamental importance for the actual use of the designed building products. In addition, the applications are intended to demonstrate the correlation that can occur between geometry and thermal path affecting the total transmittance of an envelope, and thus the concrete advantage that can be derived from the use of 3D printing, which allows a high degree of geometrical freedom.

In particular, the **fifth chapter** (*Application 1*) represents the first application and of the proposed methodology. The related case study concerns the design of an envelope component supported by parametric modelling and prefabricated with 3D printing (**RQ5**). The parametric 3D design interoperates with a thermal performance analysis using an iterative process in order to identify the best components configuration to operate in a specific external environment condition (**RQ6**).

The **sixth chapter** (*Application 2*) introduces a preliminary step to the methodological approach for designing efficient 3D printed building envelopes incorporating reused materials in the printing mixture and insulation filler. The process begins with defining the reuse design by selecting materials for recovery, followed by parametric modeling and simulation to optimize the block's shape, and finally, identifying the best settings for 3D printing production in a specific boundary condition. This approach is applied to two different case studies using a mortar with recycled glass or rubber for the printing mixture and glass fiber or cellulose for the insulation layer.

The **seventh chapter** (*Application 3*) is dedicated to the implementation of the methodology with the combined analysis of thermal performance and environmental impacts in the step concerning performance simulation. Therefore, this application explores to answer further research question **RQ7** concerning the actual sustainability of 3D printed building products. In particular, this application examines the thermal properties and environmental impacts of three additive manufacturing technologies for constructing building envelopes: large-scale 3D printing (scenario 1), 3D printing for prefabrication (scenario 2), and FDM-based formwork techniques (scenario 3). The study explores how these three approaches can be applied to create different configurations of building envelopes with specific performance targets. The iterative design and thermal analysis methodology was implemented with a single automated algorithm that closely links configuration and thermal analysis. The phase of performance study of the adopted method, in addition to thermal analysis, assesses the environmental impact of the envelope components on development. An LCA analysis has been conducted to explore the sustainable potential of cited 3D printing technologies.

Finally, the **eighth chapter** presents an experimental work on the development and prototyping of an envelope system consisting of cementitious elements that can be precast with 3D printing. Specifically, the work was conducted in response to the last two research questions. In fact, a preliminary phase focused on modifying a cementitious mixture to improve its performance according to the printing requirements, responding to **RQ8**. In addition, in order to respond to **RQ9** regarding the optimization of geometry with respect to printing requirements, 3D printing tests were conducted to adapt the initial geometry. Finally, a full-scale element was prototyped.

2. OVERVIEW ON ADDITIVE MANUFACTURING TECHNOLOGIES

2.1. Introduction

The additive manufacturing production process starts by designing a 3D model using Computer-Aided Design (CAD) software. This model is then converted into the Standard Triangle Language (STL) format and imported into slicing software, where it is "sliced" into layers compatible with the printer. At this stage, the model is intersected by a series of predefined cross-sectional planes corresponding to the thickness of the material layers. During the slicing phase, input parameters for the printing process are defined. Subsequently a Computer-Aided Manufacturing (CAM) software translates the model into a G-code, the machine language that instructs the printer on the movement to execute [8–10]. The G-Code read by the printer contains also information regarding print settings, such as layer height, fill density, print time, speed, temperature, and the x, y, and z coordinates of all points that make up the print path. After this common preparation phase, the specific additive processes vary depending on the particular method employed by the 3D printer, but is based on layering material "layer by layer" following the established path.

The current chapter aims to present the context of additive manufacturing with a focus on categories of additive processes; implied materials and their application in the construction sector answering to the **RQ1**. The chapter refers to a work published by the present writer in a dedicated journal paper [19].

2.2. Technologies

3D printing is a technique that constructs objects layer by layer from 3D model data, in contrast to subtractive manufacturing methods used in traditional manufacturing. The American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO) have collaboratively developed a standard for additive manufacturing (ISO/ASTM 52900:2015), which defines following seven categories of additive processes.

1. *Binder Jetting*: an additive manufacturing process where a liquid bonding agent is selectively applied to join powder materials.
2. *Directed Energy Deposition*: an additive manufacturing process that uses focused thermal energy (such as a laser, electron beam, or plasma arc) to fuse materials by melting them as they are deposited.
3. *Material Extrusion*: an additive manufacturing process where material is selectively dispensed through a nozzle or orifice.
4. *Material Jetting*: an additive manufacturing process where droplets of build material are selectively deposited.
5. *Powder Bed Fusion*: an additive manufacturing process where thermal energy selectively fuses regions of a powder bed.
6. *Sheet Lamination*: An additive manufacturing process where sheets of material are bonded together to form a part.
7. *Vat Photopolymerization*: An additive manufacturing process where liquid photopolymer in a vat is selectively cured by light-activated polymerization [7].

The flowchart in Fig. 2 summarizes the seven previously described additive manufacturing processes, distinguishing between those based on the binding of loose materials and those based on shape extrusion. In addition, the different technologies have been associated with types of materials and their applications.

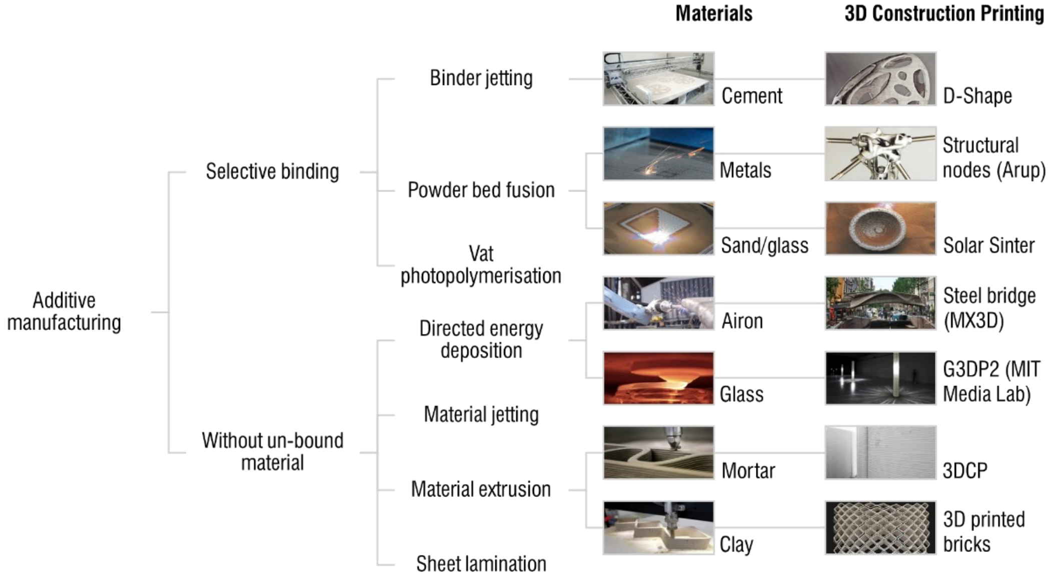


Fig. 2 - Flowchart connecting the seven categories of additive processes, the used material and practical application [16,20–29].

2.3. Materials

Additive manufacturing technologies enable the use of a wide range of materials. Nevertheless, 3D printing processes in the construction field have primarily focused on traditional materials such as cement and concrete [30]. However, the adoption of these techniques has spurred research into using composite, innovative, recycled, or sustainable construction materials [31–34]. Expanding material options would allow for adaptability in various construction situations, such as using local materials or available resources, thus supporting sustainable development [35].

2.3.1. Cement and concrete

Throughout the 20th century, reinforced concrete was one of the most widely used materials in the construction industry. Although this method contributes significantly to carbon dioxide emissions and waste material production [36,37], the majority of 3D printed constructions are still made with cement mortar or concrete. This material offers considerable potential and performance benefits [38–43]. Additionally, its use is cost-effective, as concrete production requires less energy compared to metal additive manufacturing due to lower production temperatures.

The use of 3D concrete printing for mass-market housing is becoming a reality. For instance, the company ICON has developed 3D printed houses for sale in Austin, Texas. The ground floors of the East 17th St Residences are printed using material jetting technology, which provides safer dwellings better equipped to withstand hazards and natural disasters. The second level of each house is completed using conventional construction methods [44]. Recently, S. Zivkovic and L. Lok designed and developed Ashes Cabin, a small building with a 3D printed concrete substructure. This substructure consists of 3D printed legs that allow the building to adjust to sloping terrain. This technology showcases the architectural and tectonic potential of components fabricated with a self-built large-scale 3D printer [45].

2.3.2. Metals

Metals have been used in powder bed fusion, directed energy deposition, and sheet lamination processes. Each process is suitable for different applications, with varying characteristics and limitations such as build speed or size [46]. Powder bed fusion is ideal for components with complex geometries but small sizes due to its slower process [47]. Examples include the Nematox façade node prototype made from aluminium powder [48], and the tensegrity structure lighting node by Arup, created using ultra-high-strength steel powder [26]. Directed energy deposition can utilize wire arc welding tools and wire (Wire and Arc Additive Manufacturing) to construct medium to large scale components. This technology is more suitable for the construction industry, offering a faster deposition rate and lower costs [49]. An example of this technology in the building sector is the MX3D bridge. This 3D printed stainless steel bridge spans 12 meters and is located on one of the oldest canals in central city Amsterdam. A 6-axis robotic machine created the structure from steel in mid-air using a welding arm [25,26].

2.3.3. Glass

Glass is a common material in buildings, often used for windows or entire facades. Today, it is also used as insulation, cladding, and structural components. Glass is a suitable building material due to its high compressive strength, corrosion resistance, recyclability, and thermal resistance [50]. Various studies have explored using glass in extrusion printing [51], wire-fed process [52], selective laser sintering/melting [53], CO_2 laser glass deposition [54], and stereolithography (a specific type of vat photopolymerization) [55]. The Mediated Matter group at MIT Media Lab has developed G3DP2, an additive manufacturing technology for 3D printing transparent glass structures, creating 3-meter-tall glass columns with varied surfaces. This technology uses molten glass deposition with a digitally integrated thermal control system and a four-axis motion-control system, allowing for flow control, spatial accuracy, and rapid production [24]. Additionally, 3D printed glass objects have been produced using solar-sintering technology that focuses sunlight to melt natural sand, building elements layer by layer [23,56].

2.3.4. Ceramic

Ceramic is considered a traditional construction material, commonly used in the form of earthenware, stoneware, and porcelain. Architectural components made from ceramics range from large-scale structures to bricks and tiles. Additive manufacturing can similarly produce 3D printed earthenware houses or stoneware bricks. Material extrusion, in particular, shows great potential for printing construction components of various sizes [15]. The additive manufacturing of stoneware bricks for building envelopes allows for the design of shapes that require high geometric freedom [16,57,58]. Researchers at the University of Minho's Advanced Ceramics R&D Lab (ACLab) have developed a series of prototypes for free-form ceramic walls, customizing and optimizing their shapes based on their functions. The Wave Wall prototype explores maximum vertical curvature, while the S-Brick Wall demonstrates the versatility of components when combined in different orientations. V-Bricks investigates interlocking possibilities, and the Hive Wall is a ventilated wall system with elements featuring various opening sizes to meet ventilation, shading, or visual requirements [16,59]. Wasp and MC A – Mario Cucinella Architects have designed and printed TECLA, an innovative 3D printed habitat model using locally sourced clay. The main advantage of this technology is the use of biodegradable, recyclable, and local materials that prevent waste. The large-scale building was printed in 200 hours and consists of 60 cubic meters of raw earth covering 60 square meters [60]. Institute for Advanced Architecture of Catalonia (IAAC) and WASP have also introduced a load-bearing earthen structure. This application includes a prototype of a 3D printed wall with interlocked timber elements supporting stairs, made from a mixture of clay and rice fibres [60,61].

2.4. The most used technology for 3D construction printing

Research on these technologies and the use of different materials is at varying stages of development. Specifically, research and prototyping in the construction field are predominantly focused on cement and concrete due to their widespread use and lower costs [62,63]. While 3D concrete printing is becoming a widely adopted building technology, the printing of construction components using clay, steel, or glass remains largely experimental [64]. Additionally, Material extrusion is the most commonly applied technology in this field.

3. EVOLUTION OF 3D CONSTRUCTION PRINTING AND FUTURE PERSPECTIVES

3.1. Introduction

The construction industry represents about 8% of global employment in 2023 (ILOSTAT data) [65]. Taking into account the population's growth, the construction industry is projected to increase. Meanwhile, emissions from buildings represent around 27% of total global CO_2 emissions in 2022 bringing the global estimate of energy and process-related emissions for the buildings and construction sector to around 37% [1]. In such circumstances, the implementation of innovative and sustainable technologies in the construction industry, such as 3D printing technologies, does not represent an option, but an essential need [66,67].

3D printing and additive manufacturing are based on creating objects that necessitate CAD software and exploiting a process that can add material layer by layer into accurate geometric shapes. Additive manufacturing encompasses a wide range of technologies and related applications that can bring digital flexibility and efficiency to production operations. 3D printing technologies, indeed, have become established in several industrial fields including an unprecedented increase in building construction sector during the last years [68,69].

In addition to the growing interest from various companies in 3D printing technology, academic interest in this field is also rapidly increasing. Over the past five years, scientific publications on this topic have seen an average annual growth rate of about 50%. Recently, researchers have been examining both the specific performance of 3D printing and the broader trends in AM. Existing literature reviews have focused on particular aspects such as technologies, construction methods, or materials. For instance, a major research area includes the techniques and technologies for 3D printing with metals [46,70,71]. Other research focuses on the application of 3D printing in building technologies [56,72], or the exploration of new high-performance printable materials [73–75]. Therefore, the primary limitation of the current literature is the lack of a comprehensive and informed comparison of the evolution of 3D construction printing in both the scientific and industrial domains. Additionally, there is an absence of analysis regarding both the scientific and technical aspects in the existing literature. This dual perspective is crucial as it demonstrates to companies the limits of current scientific and technical knowledge and provides researchers with valuable insights into market trends and demands. Moreover, this information is essential for a broad overview of the research conducted, enabling future studies to be strategically designed for significant global impact. Furthermore, effective tools are needed to support the growth of the construction sector, which has shown inherent inertia over recent decades. Thus, the proposed comparison is beneficial for examining the relationship between research and companies in innovative areas with high potential, such as 3D construction printing.

This chapter presents an in-depth investigation of current advancements in 3D construction printing, emphasizing the comparison and differences between academic research and industry progress. This comparison provides a comprehensive overview of how academia and the professional sector operate differently, identifying both gaps and potentials. Specifically, an initial analysis examines additive manufacturing by considering technology, materials, and existing applications in the construction sector. Subsequently, another investigation focuses on the technological evolution and application in 3D construction printing, particularly on 3D printed buildings, comparing academic research with the construction market. The described work has as its main reference a work published by the present writer in a dedicated journal paper [19].

The main novelty of this section lies in a critical analysis of the technological evolution and existing gaps to highlight the shortcomings of the technologies. The work focuses on two main objectives derived from research questions: **RQ2** comparing the evolution of 3D construction printing in both scientific research and the construction market; **RQ3** outlining a roadmap and future directions for the development of 3D printing technology in construction companies and research.

The chapter follows these steps: (I) analyzing the parallel development of interest in academic research and the construction market; (II) comparing different types of additive manufacturing and materials that can be used, as well as recent applications of these technologies in the construction industry; (III) investigating the limitations and future opportunities of the combined use of materials and additive manufacturing techniques.

As a result, the investigation highlights the existing gap and future interests of both the academic world and industry, providing a useful roadmap towards the digital transition of the construction sector.

3.2. Research methods

The proposed approach aligns with Snyder's four principles for scientific reviews [76]: designing the review, conducting the review, analysis, and writing up the review. Additionally, the analysis has been revised to incorporate charts, maps, and flowcharts utilizing bibliometric analysis and data visualization techniques. The choice to combine Snyder's four-point methodology with bibliometric analysis stems from the necessity of rendering processed data - spanning various disciplines - comparable in terms of temporal evolution, geographic distribution, and thematic focus.

Bibliometric analysis facilitates the intuitive comprehension and comparison of both qualitative and quantitative data. These methods serve to direct researchers toward the most impactful works and systematically map the research field, ensuring a transparent and reproducible review process. They contribute to establishing a level of objectivity in evaluating scientific literature [77].

3.2.1. Design of the review

The initial stage involves designing the review, which entails defining a specific purpose and research questions. In essence, the research investigation revolves around two primary objectives, each comprising a series of research inquiries.

I) Comparative analysis of the evolution of 3D construction printing in both scientific research and the construction market. The research inquiries pertinent to the first objective (RQ2) encompass:

- How extensive has the research been over time and across the globe?

- What thematic areas (topics and keywords) have been the focus of research?
- To what extent is there international interest from companies?
- Does the current research knowledge adequately support companies' activities?

II) Establishing a roadmap and outlining future directions for the development of 3D printing technology in construction companies and research. The research inquiries pertaining to the second objective (RQ3) include:

- What are the significant milestones in the development of 3D construction printing technology?
- What technical challenges lie ahead for future development?

3.2.2. Conduction of the review

The second step involves identifying keywords and search engines to select relevant outputs. In the academic field, outputs were collected through a bibliometric analysis. Database searches were conducted on Scopus, Elsevier's abstract and citation database, Dimensions, and CumInCAD by selecting specific and pertinent subject areas and querying the keywords. The advanced search utilized field codes (e.g., TITLE-ABSTRACT-KEYWORD), wildcards (e.g., *), proximity operators, and Boolean operators (e.g., "AND", "OR"). The quality of the search process and data selection was verified by sampling random data and assessing their relevance.

Scopus offers extensive coverage of scientific production and has a fast-indexing process [78]. It is the largest abstract and citation database of peer-reviewed research literature across various fields, including science, technology, medicine, social sciences, arts, and humanities, covering over 20,000 peer-reviewed journals [79]. Dimensions is an inclusive abstract and indexing database that allows users to explore connections among a wide range of research data. By 2024, Dimensions included more than 140 million publications [80]. CumInCAD is a Cumulative Index of publications in Computer Aided Architectural Design [81], serving as a significant resource for research related to computer-aided architectural design, architectural computing, computational design, and design technology. Hence, it was selected as a source of data specifically related to architecture.

The use of 3D printing techniques in the construction market was investigated through market analysis, identifying companies and their related applications. Buildings produced using 3D printing processes were identified through systematic research conducted using the "news" section of the Google search engine for each year from 2000 to the present. The "custom range" tool and keywords such as '3D printing,' 'building,' and 'house' were explored. Mapping the 3D construction printing community began with identified companies, and the dataset was further expanded by including businesses mentioned in the reviewed articles.

3.2.3. Analysis

The data analysis aims to process, interpret, and graphically display the trends in the collected data using bibliometric analysis and data visualization techniques (charts, mapping, and flow charts). Bibliometric analysis examines academic research from *temporal*, *geographical*, and *thematic* perspectives.

For the construction industry, charts and maps are employed to analyze and visualize data. Initially, the 3D construction printing market is explored by mapping 3D printed buildings constructed by companies worldwide. Following this, a global overview of the main companies involved in 3D printing is provided, focusing on both the founding of the companies and the establishment of specific divisions dedicated to producing 3D printed buildings.

3.2.4. Writing up the review

The final step involves writing the review, emphasizing the dual investigation of both scientific and technical aspects. Additionally, it highlights the importance of a focused investigation into the most commonly used technologies and materials. A comprehensive overview of the entire framework of the proposed bibliographic research is presented in Fig. 3.

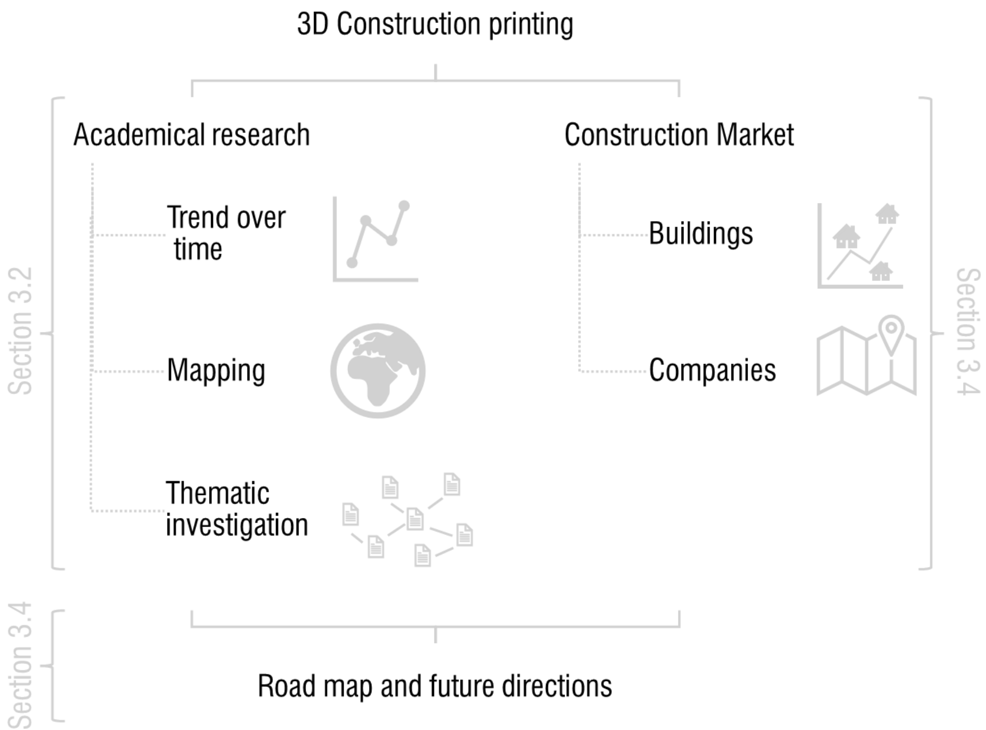


Fig. 3 - Bibliographic research framework.

3.3. Analysis of scientific research outputs

The research has focused on material extrusion, the most widely applied technology in the building sector, using materials such as cement, concrete, and clay for 3D construction printing. A bibliometric analysis has been conducted to showcase the knowledge in this research field by employing a set of mathematical and statistical methods [82]. The results provide a holistic view of the research area, identify knowledge gaps, and position contributions within the field [83].

Data have been organised and displayed in charts using Microsoft Excel (Microsoft® Excel® for Microsoft 365 MSO). XLSTAT software has been employed to perform descriptive statistics of data samples [84]. Part of the bibliometric analysis was conducted using the R-tool BiblioShiny, which provides multiple visualizations and graphs from a web-based interface [85]. The computer program VosViewer was used to produce visualizations of network relationships [86,87] and to analyse the co-occurrence relations between authors' keywords.

The main descriptive information about the data sample has been summarized in Tab. 1 using BiblioShiny [88]. Specifically, a total of 1856 documents were analysed (1080 from Scopus; 508 from Dimension; 268 from CumInCAD).

Tab. 1 – Dataset's descriptive information.

Description	Results
Main Information about Data	
Timespan	2000:2021
Sources (Journals, Books, etc)	681
Documents	1856
Average years from publication	3.04
Average citations per documents	12.37
Average citations per year per doc	2857
References	36913
Document types	
Article	628
Book chapter	124
Conference paper	287
Conference review	33
Review	64
Document contents	
Keywords Plus (ID)	7164
Author's Keywords (DE)	3542
Authors	
Authors	3786
Author Appearances	5401
Authors of single-authored documents	619
Authors of multi-authored documents	3167
Authors collaboration	
Single-authored documents	715
Documents per Author	0.49
Authors per Document	2.04
Co-Authors per Documents	2.91
Collaboration Index	2.79

To summarize, the following three subsections present different investigations and their respective results.

The first section constitutes a preliminary investigation that introduces trend charts for research outputs on 3D printing. It showcases the global interest in 3D printing and compares it to the interest in 3D printing within the construction sector and other industries. Additionally, it delves into 3D printing in the building sector by comparing the percentage of publications on this topic to the total number of publications in the field.

The subsequent global overview analysis maps the global application of 3D printing by identifying the countries associated with the origins of the publications and highlighting their relative academic impact.

Finally, the scientometrics investigation applies scientometric methods, such as WordCloud representation, co-occurrence analysis, and hierarchical clustering, to provide an overview of the main topics and sub-topics within the field.

3.3.1. 3D printing: trend over time

The automation of construction and the use of 3D printing technology are becoming increasingly attractive to the academic world. In this context, bibliometric analysis is an effective tool to understand the scientific proliferation of 3D printing. This trend can be observed by analysing the frequency of publications on "3D printing construction" and comparing these results with publications across the entire field of additive manufacturing.

This initial analysis considers the number of results from querying "3D printing" (searched within Article title, Abstract, Keywords). The trend of publications on 3D construction printing is then tracked by investigating subjects such as Engineering, Materials Science, Computer Science, and Environmental Science, while excluding incompatible subject areas with 3D construction printing. These filters help focus on relevant information. The specific search queries used are: ("3D print*" AND (construction OR concrete OR cement)) OR "3D construction printing", searched within Article title, Abstract, Keywords.

After determining the trend for 3D printing both globally and specifically in the construction sector, it is compared with trends in other application fields. For example, biomedical applications of 3D printing were identified by querying "3D printing" AND (biomed* OR medicine) and limiting the subject areas to Medicine, Biochemistry, Chemistry, and related fields (searched within Article title, Abstract, Keywords).

Fig. 4 illustrates the annual number of publications on 3D printing and the publication trends related to 3D printing between 2000 and 2021. The results indicate that global trends for general applications, 3D printing in building construction, and 3D printing for biomedical applications are all rapidly growing. However, the increase in research within the field of building construction is slower compared to other sectors. The trend shows a gradual increase from 2000 to 2014, followed by a faster increase after 2014. Although 3D printing applications in building and construction are still limited compared to overall 3D printing uses, the significant growth in recent years suggests a promising future.

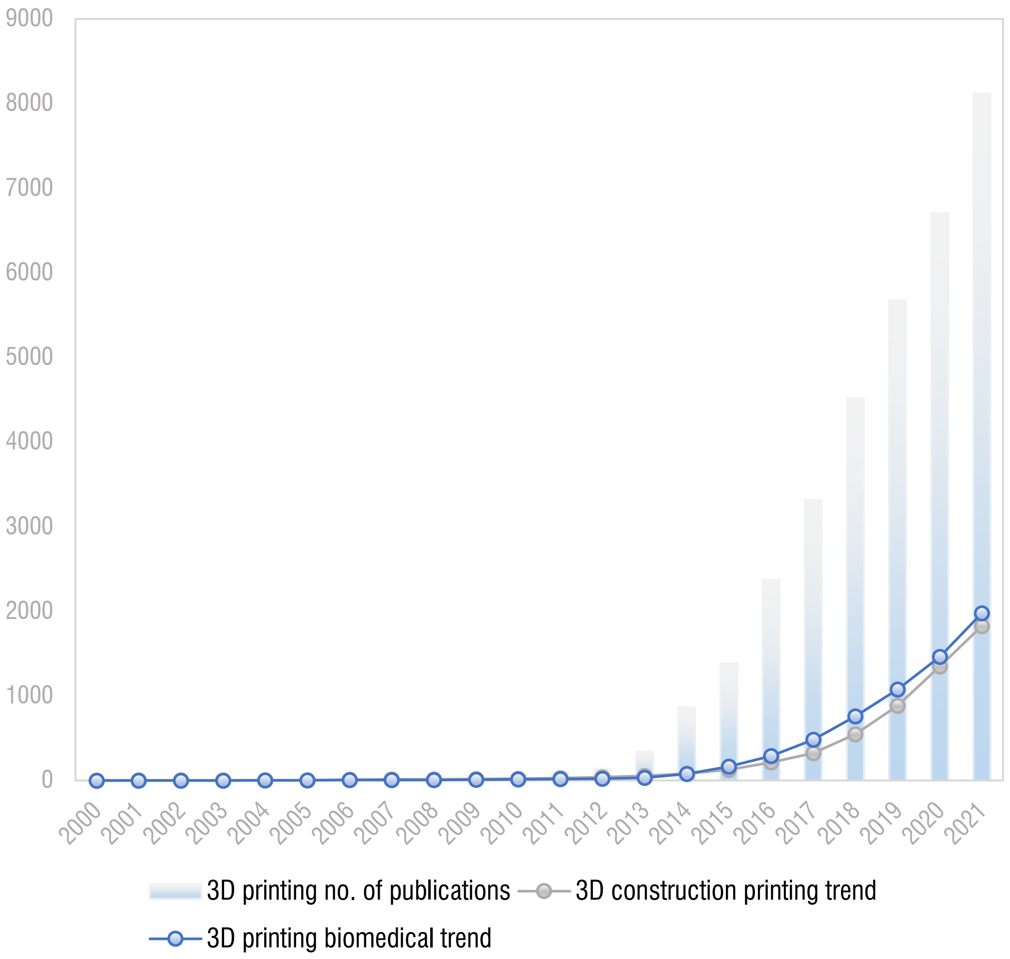


Fig. 4 - Publication's trend comparing global 3D printing interest, 3D construction printing technologies and biomedical 3D printing from 2000 to 2021.

To assess the impact of 3D printing technology on the building and construction sector, the observed trend was compared with the overall volume of general publications in building construction (Fig. 5). The keywords used for searching the entire set of publications in this area were "Building" OR "Construction" OR "Construction engineering," filtered by the subject area "Engineering."

The investigation reveals that 3D printing constitutes only 0.06% of current publications in the construction industry. A notable observation is the rapid increase in the growth rate of 3D printing scientific publications, which has shown an exponential trend since 2016.

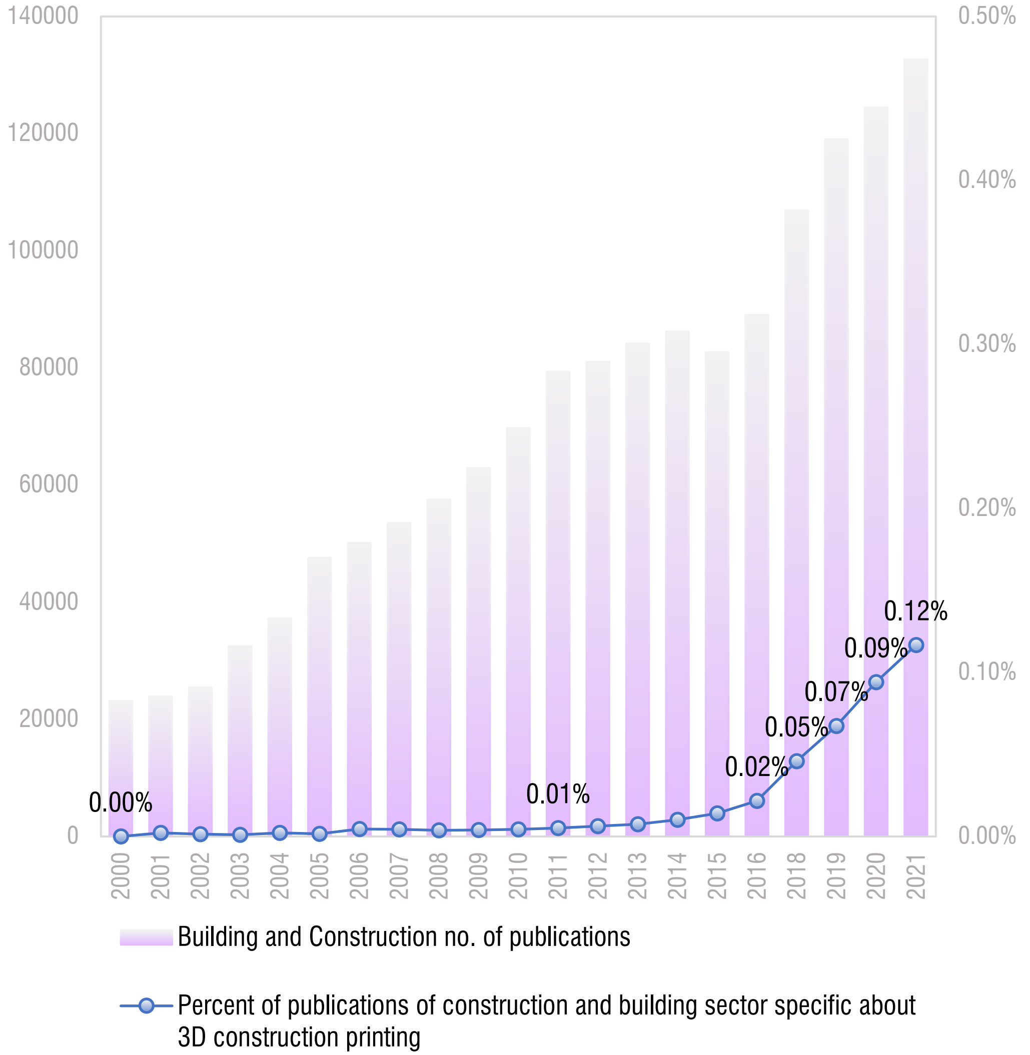


Fig. 5 - Percent of publications about 3D construction printing compared to the total number of publications in construction and building sector.

3.3.2. Mapping of academic research

Another investigation examines the origin of the publications to understand the impact of 3D printing on the research output of each country. A detailed map has been created to display the number of documents produced by each country (Fig. 6). The countries with the highest number of publications are the United States (275), China (237), and Germany (97). Additionally, the figure illustrates international collaboration in this scientific production, with red curves representing collaborations between different countries. These connections on the country collaboration map were generated using BiblioShiny for bibliometrix.

Regarding the impact of existing research, the number of citations by country provides valuable insights. Initially, data on the total citations of each paper were examined using descriptive statistical analysis. The results of this analysis are presented in Tab. 2.

Tab. 2 - Results of the descriptive statistics.

Mean	**Standard deviation (n-1)**	**Coefficient of variation**	**Maximum value**
21.2	358.2	16.9	2197

Moreover, the frequency distribution shape follows a Pareto distribution with an extreme upper outlier, as identified by the Dixon outlier test. These findings indicate that the citation analysis by country is skewed, with a few of the oldest works receiving a disproportionately high number of citations compared to more recent articles. To address this imbalance, the analysis was adjusted by normalizing the total number of citations per year (TC per year). The resulting impact of scientific production per country, measured by the most cited works per year, is shown in Fig. 7. This adjusted analysis confirms the top-ranking positions of China (2196.7 TC per year), Australia (151.4 TC per year), and the United States (1025.7 TC per year), holding the first, second, and third positions, respectively. It also highlights that some countries, such as Australia, have a greater impact despite producing fewer articles than others, like Germany (841.3 TC per year).

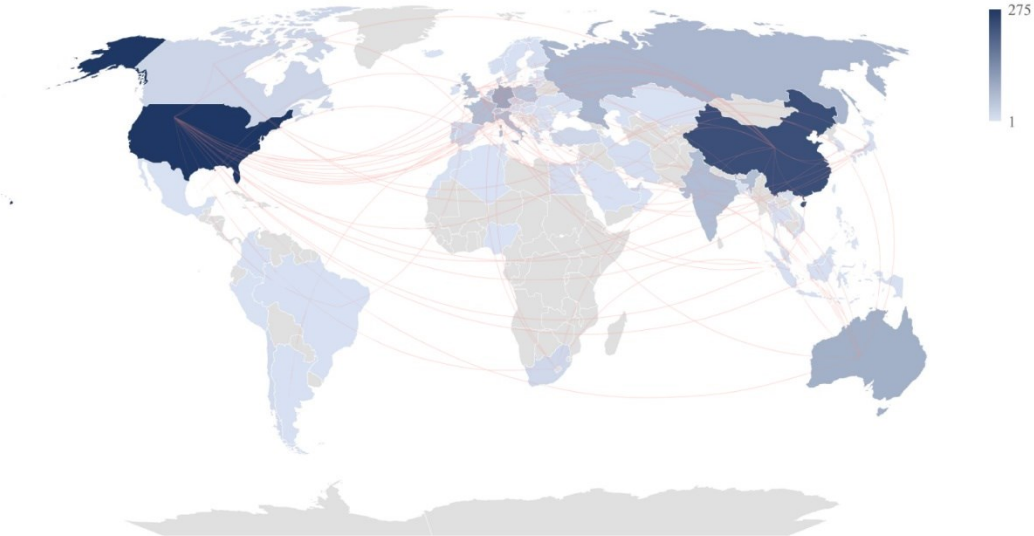


Fig. 6 - Publications by country [19].

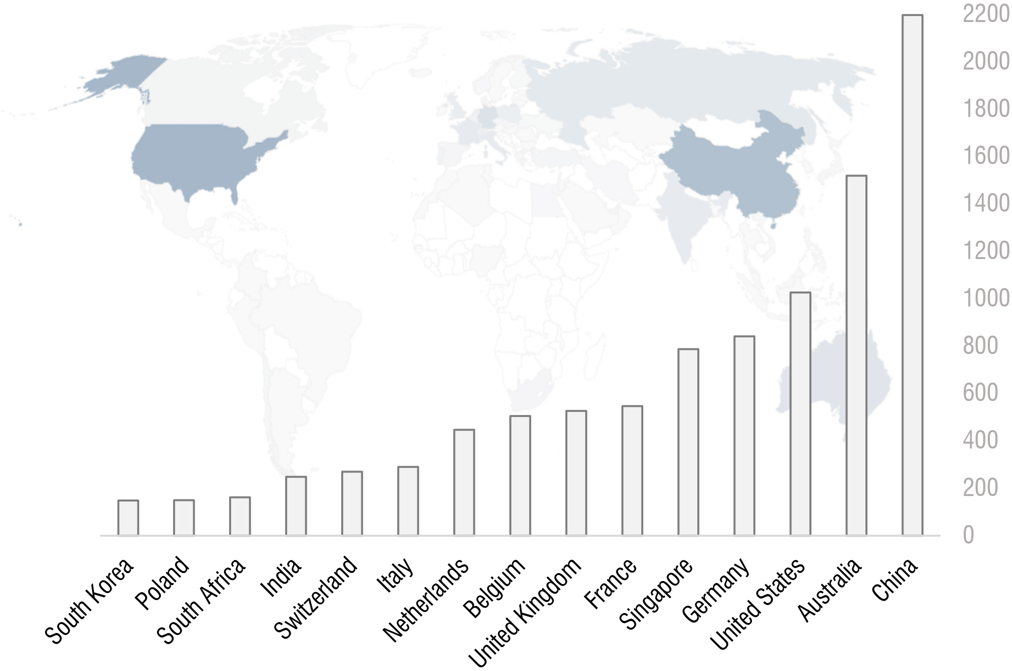


Fig. 7 - Most cited country of research documents published according to the total number of citations per year.

3.3.3. Thematic investigation

The thematic investigation elucidates the internal relationships among various classes of concepts (including topics, keywords, or Keywords Plus) and graphically represents the performed analysis [89]. To this end, the WordCloud of the most used Keywords Plus provides an overview of the most significant concepts. Following this, a conceptual structure is illustrated through a network visualization, such as the co-occurrence network of authors' keywords. Additionally, a correspondence analysis is employed to display the frequent authors' keywords in a dendrogram, enabling hierarchical clustering and confirming the relationships among different classes of concepts. To avoid obvious connections and results, the querying keywords used to find the dataset were removed from the cloud before running the analyses.

Fig. 8 highlights the WordCloud of the most used Keywords Plus, which are the words or phrases that frequently appear in the titles of an article's references but not necessarily in the title of the article itself. According to Kroeger et al. (2005), the analysis using Keywords Plus can capture an article's content with greater depth and variety [90]. In the achieved WordCloud for 3D construction printing, the following words are prominent: I. Additives, II. Compressive strength, III. Mechanical properties, and IV. Cementitious materials.

Various terms highlight the close connection between 3D printing technology and cementitious materials. Several words are related to different cementitious materials and their characteristics. This additional investigation aligns with previous results regarding the most used technologies and materials (concrete) for 3D construction printing.

Another inference from the WordCloud is the need to improve and adapt concrete material for 3D printing. Prominent terms include "mixtures" and "additives," as well as "fly ash" and "geopolymers." Specifically, fly ash leads to high-early strength, high workability, and low porosity, while geopolymers are commonly used as additives to improve the mechanical properties and printability of mixtures [91–94].

Additionally, the frequent occurrence of the word "reinforcement" underscores one of the major technological challenges in 3D concrete printing, namely the integration of reinforcement [95,96].

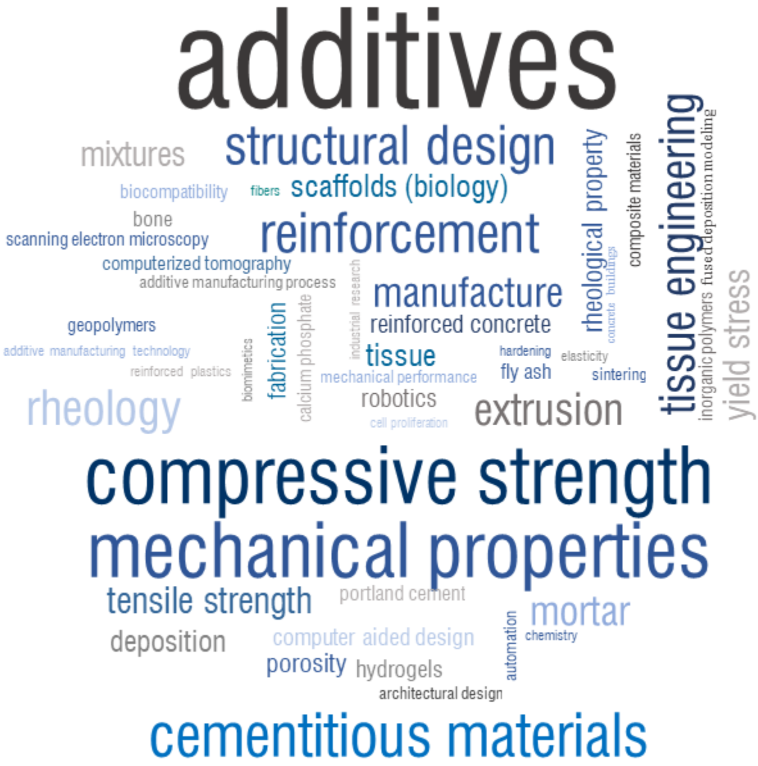


Fig. 8 - Top 50 Keywords Plus on 3D construction printing. Software: BiblioShiny and XLSTAT.

The network visualization of the conceptual structure illustrates the frequency of co-occurrence of terms from a text corpus. Consequently, the co-occurrence of words can indicate semantic proximity among topics [90]. The co-occurrence relationships among authors' keywords have been analyzed and shown through science mapping (Fig. 9). In this figure, keywords, divided into clusters, are represented by circles connected by lines that indicate relationships among keyword nodes. The size of each bubble is proportional to the number of citations of the item, and the position reflects the centrality of the topics.

The network consists of 61 items divided into six clusters, connected by a total of 544 links. As expected, the "Additive manufacturing" bubble serves as a common connection point among the different clusters. It belongs to the yellow cluster, which contains other 3D construction printing topics. The blue and green clusters, which are strongly connected, represent the rheological properties of printable materials and, in particular, printable cement paste. The light blue cluster represents the connection between mechanical properties and other material characteristics such as porosity or thermal conductivity. The last two clusters, red and purple, are less connected to the others. The red cluster includes topics related to technologies, while the purple cluster contains marginal topics, such as reinforcement or rapid prototyping, represented as orbital bubbles.

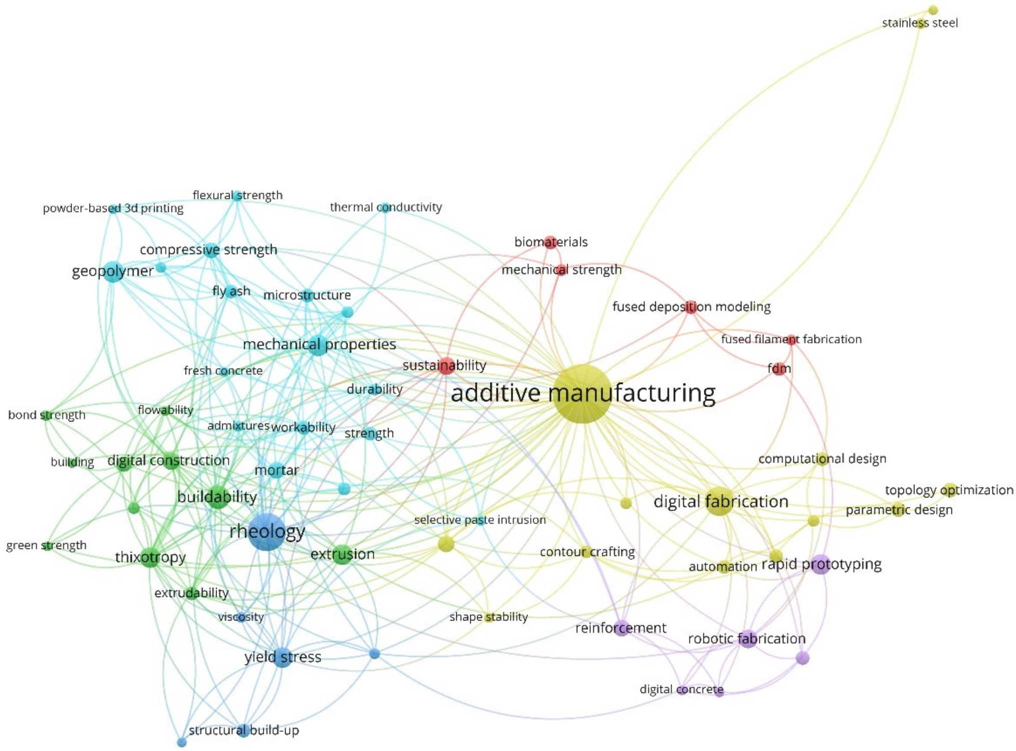


Fig. 9 - Co-occurrence keywords network. Software: VosViewer [19].

In conclusion, the factorial analysis represents the dataset in a lower-dimensionality space, allowing the identification of subfields of topics. The applied dimensionality reduction methodology is Multiple Correspondence Analysis (MCA). Fig. 10 displays the dendrogram of the topics and confirms the relationships among various classes of topics identified in the co-occurrence analysis. For instance, printable properties of cementitious materials and rheological properties are grouped together. Moreover, the relative positions of certain words (such as "Rheology" and "Thixotropy") are similarly close in both the co-occurrence network and the dendrogram, confirming the relationship among these themes. The height of the connections in the dendrogram measures the distance among words, using a scale proportional to the number of articles that discuss them together. Other connections reveal the proximity of issues that are frequently addressed together.

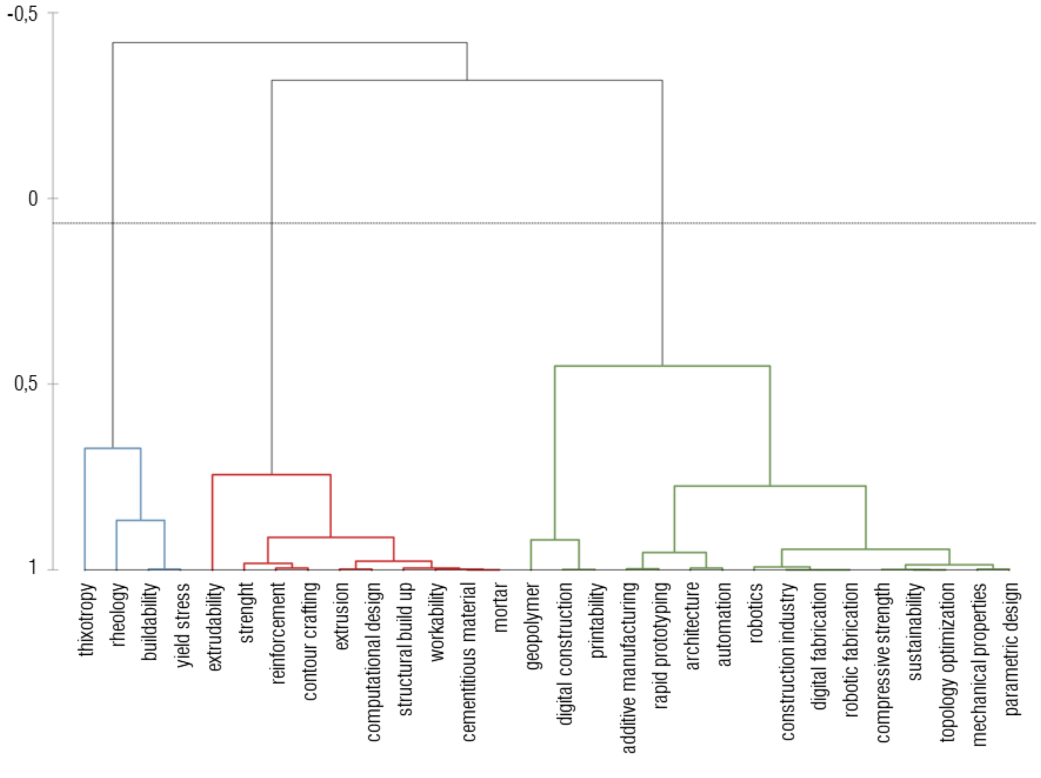


Fig. 10 - Topic dendrogram. Software: BiblioShiny and XLSTAT.

3.4. The 3D printing construction market

Interest in 3D printing applications within the construction industry has seen exponential growth in recent years. To investigate the evolution of the construction market, two analyses were conducted.

The first preliminary investigation identifies specific trend charts and maps the production of 3D printed buildings over the past few years. This analysis provides an overview of the initial demonstrations of 3D printed buildings worldwide, carried out by various construction companies.

The second analysis offers a global overview of the main companies involved in this field. It includes temporal information on the founding of these companies and the development of specific manufacturing divisions for 3D printed buildings. This helps to determine whether each company evolved over time to include 3D printing or was established specifically to produce 3D printed buildings.

3.4.1. 3D printed buildings

The 3D construction printing market is rapidly expanding, estimated at USD 3 million in 2019 and projected to reach USD 1,575 million by 2024 [97]. The number of 3D printed buildings around the world increases every year. Therefore, a survey of all the 3D printed buildings developed until 2022 has been conducted using the Google search engine. In particular, the keywords '3D printing' 'building' 'house' have been queried in the section News using the tool custom range for each year from 2000 to 2022.

The number of 3D printed buildings worldwide is increasing annually. A survey of all 3D printed buildings developed until 2022 was conducted using Google, querying keywords '3D printing,' 'building,' and 'house' in the News section with a custom date range for each year from 2000 to 2022.

The first application of material extrusion technology in construction was proposed by Dr. Behrokh Khoshnevis with the Contour Crafting (CC) technology. Developed at the University of Southern California and introduced at the 19th International Symposium on Automation and Robotics in Construction (ISARC) in 2002, CC involves the contour extrusion of vertical concrete formwork, later completed with concrete casting [4,5].

In 2010, the first 3D printed building resembling a house was presented at the Milan Triennale. Created with the D-shape technique, which uses binder jetting, the stone-like object was designed by Marco Ferreri and required two weeks to print. The building element, made entirely of cement, measures 2.40 m in width, 4 m in length, and 3.50 m in height [98].

Since then, numerous technologies and ambitious projects have emerged [14,99–101]. Fig. 11 provides an overview of 3D printed buildings worldwide, with China, the United States, the Netherlands, and Italy leading in the number of such structures.

Today, the sophistication of these technologies enables the production of fully 3D printed houses in a few days. For instance, the first European habitable property with load-bearing walls made using 3D printing is part of Project Milestone in Eindhoven. Developed by Saint-Gobain Weber Beamix in partnership with Eindhoven University of Technology, Van Wijnen, Vesteda housing corporation, the Municipality of Eindhoven, and Witteveen+Bos, the Dutch house features 94 m^2 of floor area with living space and two bedrooms. It required 120 hours of printing time and has been occupied since April 2021 [102].

Fig. 12 showcases a selection of 3D printed buildings, highlighting common features such as single-story designs (with exceptions integrating traditional horizontal structures), the use of cementitious materials and the use of clay materials such as "Tecla", "Gaia" and “Tova” buildings [60].

Fig. 11 - Mapping of 3D printed buildings by construction companies around the world [44,103–115].

Fig. 12 - Principal 3D printed buildings [44,60,103–118].

3.4.2. The interests and arising of new companies

The analysis of companies that realize 3D printed buildings provides insights into the evolution and trajectory of the technical sector. This investigation highlights which companies were already in existence and created new departments specifically for 3D printing, and which were established explicitly to utilize this technology.

Among the 71 companies examined, 46 were founded specifically to develop 3D printed technologies, while 25 existing companies upgraded their operations to include this production process.

Tab. 3 lists the investigated companies, including their countries of origin, year of foundation, and the year they began working on 3D printed technologies. The dataset of the 3D construction printing community was compiled through the applications previously analyzed, visits to companies' websites, and review articles.

Tab. 3 - Companies involved in the 3D construction printing.

Companies	Foundation	3D Printing	Country	References
3D Concrete by Betonindustrie Brievengat	2021	2021	Curaçao	[119]
3DPC Group	2021	2021	Denmark	[120]
14 Trees	2016	2016	Malawi	[121]
ABB	1995	2019	Switzerland	[122]
Acciona	1997	2016	Spain	[123]
Aeditive	2019	2019	Germany	[124]
Alquist	2020	2020	USA	[125]
AMT-SPETSAVIA Group	2009	2013	Russia	[107]
Apis Cor	2015	2015	USA	[111]
Arup	1946	2014	UK	[26]
Autoconz	2018	2018	Indonesia	[126]
Bam Nuttal	1865	2019	Netherlands	[127]
Basler and Hofmann	1963	2019	Switzerland	[128]
BE More 3D	2016	2016	Spain	[113]
Beijing Huashang Luhai Technology	1989	2016	China	[129]
Besix 3D	2017	2017	UAE	[130]
Betabram	2012	2012	Slovenia	[131]
Black Buffalo	2020	2020	USA	[132]
Branch Technology	2013	2013	USA	[133]

Bruil	1910	2015	Netherlands	[134]
Cazza Construction Technologies	2016	2017	USA	[135]
Citizen robotics	2020	2020	USA	[136]
COBOD	2017	2017	Denmark	[137]
Concreative	2019	2019	UAE	[138]
Construction 3D	2017	2017	France	[139]
Contour Crafting Corporation	2006	2006	USA	[140]
CyBe Construction	2013	2013	Netherlands	[141]
Emergent	2019	2019	USA	[142]
Emerging Objects	2013	2013	USA	[143]
Havelar	2024	2024	Portugal	[144]
HeidelbergCement	1872	2015	Germany	[145]
Huashangluhai	1989	2016	China	[110]
Hyperion robotics	2019	2019	Finland	[146]
ICON	2017	2017	USA	[44]
Imprimere AG	2015	2015	Switzerland	[147]
Incremental3D	2017	2017	Austria	[148]
Italcementi	1927	2018	Italy	[149]
Ka Bina	2021	2021	Malaysia	[150]
KAMP C	2003	2019	Belgium	[151]
Lafarge	2015	2016	France	[152]
L&T Construction	1938	2019	India	[153]
Lifetec Construction Group Inc	2017	2017	Canada	[154]
Mobbot	2018	2018	Switzerland	[155]
Monolite UK (D-Shape)	2006	2006	UK	[28]
MudBots	2019	2019	USA	[156]
MX3D	2014	2014	Netherlands	[25]
Peri	1969	2018	Germany	[106]
Pikus 3D Concrete	1999	2021	USA	[157]
Power2build	2021	2021	USA	[158]
Printed Farms	2019	2019	USA	[159]
Qorox	2019	2019	New Zeland	[114]
Rohaco	1972	2015	Netherlands	[160]
Rupp Gebäudedruck	2020	2020	Germany	[112]
Scoolpt	2019	2019	Czechia	[161]
Serendix	2021	2021	Japan	[162]
Siam cement group	1913	2014	Thailand	[163]

Sika	1910	2017	Switzerland	[164]
SimplyForge Creations	2018	2018	India	[165]
Skidmore, Owings & Merrill (SOM)	1936	2015	USA	[166]
SQ4D Inc.	2015	2015	USA	[167]
StrongPrint 3D	2021	2021	Canada	[168]
TamVinci	2021	2021	UAE	[169]
Total Kustom	2014	2014	USA	[117]
Twasta	2016	2016	India	[170]
Twente Additive Manufacturing (TAM)	2018	2018	USA	[171]
Vertico	2017	2017	Netherlands	[172]
Wasp	2012	2015	Italy	[60]
Weber Saint-Gobain	1985	2015	France	[173]
WinSun	2003	2004	China	[108]
Witteveen + Bos	1958	2017	Netherlands	[174]
XtreeE	2015	2015	France	[175]

Observing the data, the USA has the highest number of companies (18) involved in 3D construction printing, with most of these American firms being established specifically for this purpose. This trend is reflected in the number of 3D printed buildings in the country (19). The USA, along with China (14), has the largest number of such constructions. Although only three companies in China focus on 3D construction printing, they have a significant impact and many local applications.

The disparity in the number of companies between the USA and other countries is notable. The Netherlands is the second country in terms of the number of companies, with seven. Another observation is the timeline when companies began working on 3D printing. Many of these companies were established between 2014 and 2015, a period when 3D construction printing started to gain traction.

3.5. Discussion

The research investigation has focused on two main objectives, each addressing a set of research questions. The following sections present the results from the previous analyses, addressing these two aspects: (I) comparing the evolution of 3D construction printing in both scientific research and the construction market; and (II) outlining the roadmap and future direction for the development of 3D printing technology in construction companies and research. Each subsection discusses the six research questions related to these objectives. Finally, the limitations of the research methods are discussed.

3.5.1. Comparison of the research and companies' advancements in 3D construction printing

The present section discusses and responds to the first four research inquiries presented in the research methodology of this chapter.

I) Development over time and in the world of scientific research

The temporal investigation has demonstrated an increasing trend in 3D printing publications and the development of 3D printed buildings, even when compared to other application fields. The geographical analysis provides a global overview of the application of 3D printing by mapping the locations of countries where the publications originated and highlighting their relative academic impact. This preliminary analysis underscores the importance of the topic, given the rapidly growing interest.

II) Scientific research: thematic areas

The thematic analysis has highlighted the most investigated topics in 3D construction printing within scientific research and their interconnections. This method has been effective in presenting an overview of the current state of research across different aspects. It allows us to identify the most explored topics and the macro-areas they belong to.

First, the cluster analysis and co-occurrence keywords network analysis have helped to identify three main macro-areas through a qualitative evaluation of the research products. Second, more specific clusters are defined by the co-occurrence keywords network analysis. Third, an additional qualitative study, using word clouds and reading the articles, has identified the themes and disciplinary origins of the publications. Tab. 4 classifies the macro-areas, core themes, related clusters, and their disciplinary origins.

A comparison of the results indicates that 3D construction printing themes have been largely addressed within the first macro-area of chemical/material science to develop suitable mixtures for additive manufacturing. Consequently, materials development can be identified as a key research macro-area. The keyword analysis highlights terms related to the optimization of cementitious materials and rheological properties. To this end, innovative compounds that meet the characteristics of an extrudable material have been developed.

Another macro-area of investigation concerns structural performance, which initially focuses on printable materials but is increasingly concerned with the printed product as well. The third macro-area includes the technological and digital transition aspects of construction. Many keywords refer to digital technologies, digital fabrication, robotics fabrication, automation, and parametric design.

Tab. 4 - Macro-areas, clusters, themes, and the disciplinary origins.

Macro-area	Cluster	Themes	Disciplinary Origin
Printable material development	Rheological properties	Rheology Extrudability Viscosity Tixotrophy Flowability	Material scence
	Material characteristics	Microstructure Thermal conductivity Additives Fresh concrete	Chemistry
Structural performance		Mechanical properties Compressive strength Flexural strength Durability	Structural engineering
Construction technology and digital transition	3D construction printing topics	Additive manufacturing Selective paste intrusion	Engineering
		Digital fabrication Automation	Automatic control science
	Technologies topics	Shape stability Computational design	Architecture
		Robotic fabrication Digital concrete Reinforcement	Construction engineering

III) Companies' interest at international level

The proposed review highlights the undeniable potential of 3D printed construction, as evidenced by the significant development of 3D printed structures worldwide and the growing interest from companies. However, this rapid growth and development bring several unresolved limitations and research questions.

The primary limitations of 3D printed construction involve size, construction time, and performance, which are still not comparable to traditional techniques [176,177]. For example, the difficulty of incorporating reinforcements directly during the printing phase limits the structural performance of the components [30,178]. As a result, the number of floors in most cases remains limited. Another significant issue is printing horizontal surfaces such as slabs, which remains problematic and is often resolved by using prefabricated components [12,13]. Typically, horizontal structures in printed constructions are made using traditional building techniques. Therefore, construction time could be further reduced by enhancing the capability to print wide and thick layers of material.

Additionally, several research questions regarding the actual performance and sustainability of these structures are emerging. Despite the numerous 3D printed constructions being built globally, there is a considerable lack of scientific knowledge on their actual performance, durability, sustainability, life cycle environmental impact, and circular design [176]. Companies' interest is often driven by marketing benefits or prospects for quick profits. The risk of these approaches is the production of structures that are not currently supported by solid knowledge and experimental tests with a scientific approach.

IV) *Support of companies' activity by research knowledge*

The proposed comparison highlights fundamental differences between academic research and the approach of construction companies toward the introduction of additive manufacturing technologies. 3D printed construction has gained media popularity as a solution for affordable, quickly producible housing worldwide [177]. Consequently, expectations have risen rapidly. However, research on the performance and effectiveness of such construction has not adequately supported the spread of the technology. Therefore, the construction market faces significant challenges, including social adaptation, investment costs, production control, lack of experience, regulations, and innovation in production equipment and processes.

Fig. 13 shows an overlap of the mapping of publications by country (blue colour gradation) and the number of companies working in 3D construction printing in different countries. It is evident that 3D construction printing companies are concentrated in Europe and America, though their presence is also spreading to countries where research is still developing. Moreover, this comparison helps understand the gap in specific countries between companies' interest in the technology and the scientific knowledge and ongoing research in the local academic area.

Even though the distribution of publications by country aligns with the distribution of companies involved in 3D construction printing, the review underscores a significant difference between the business production needs and the scientific knowledge.

Scientific research has demonstrated the various potentials of different additive manufacturing technologies in the construction industry. However, almost all existing large-scale 3D printed constructions are produced using material jetting technologies and cementitious materials. This trend can be explained by the significant potential for optimizing costs and production times. Moreover, despite its innovative nature, this technology is more compatible with conventional construction materials that have already been widely tested. Additionally, the broad spectrum of existing cementitious mixtures allows for the refinement of characteristics and compositions of printable materials [178].

On the other hand, other additive manufacturing techniques, when combined with different materials, require solutions to become more suitable for the construction field. The number of publications found in the literature indicates advancements in the technological development and progress in the scientific investigation of these techniques.

Fig. 13 - Comparison of the blue color gradation representing each country's publication output with the number of companies engaged in 3D construction printing.

3.5.2. Roadmap

The following subsection responds to the research inquiries related to the significant milestones in the development of 3D construction printing technology outlining a roadmap. The roadmap (Fig. 14) emphasizes the future's challenges.

- **1941**: William E. Urschel patented the 'Machine for Building Walls,' one of the earliest extrusion machines for construction.
- **1996**: Research into 3D printing introduced the Contour Crafting technology, a material extrusion technology for cement and concrete.
- **2005**: The D-Shape technology, a large-scale binder jetting technique, was patented.

- **2014**: Global research interest in 3D construction printing began to surge.
- **2015**: The first buildings were 3D printed.
- **2016**: Numerous companies worldwide started showcasing their 3D printed buildings.
- **Future Research and Technical Challenges**: Focus on conscious construction design for 3D printable structures, addressing broad-spectrum sustainability and performance improvement.

As a result, the review highlights that scientific research is lagging behind business advancements, which are quickly developing new design projects and numerous 3D printed constructions. Consequently, the scientific challenge in the coming years will be geared toward filling this significant knowledge gap. This effort will help guide the construction industry toward the informed adoption of design principles and construction techniques, facilitating the sector's transition to digital innovation.

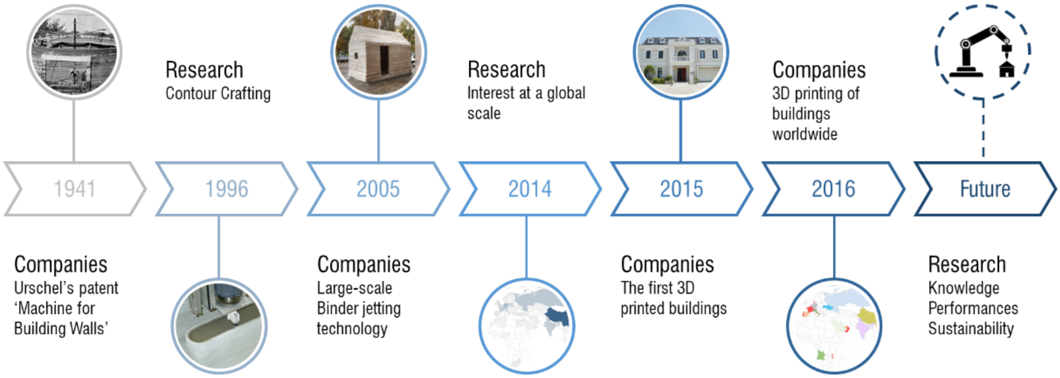


Fig. 14 - Roadmap and future direction of 3D construction printing [2–4,109,182].

3.5.3. *Future direction*

Combining thematic investigation with company analysis yields the following valuable insights (Tab. 5): I) most researched topics; II) most researched topics with unresolved questions; III) topics not yet addressed but of interest to both academics and companies.

Tab. 5 - Thematic survey and results of company analysis.

Efficient/popular technologies	Topics with open questions	Topics not yet deepened
Material extrusion of cement-based material	Marketable production	Acoustic performance
Material extrusion of earthenware	Reinforcement	Seismic resistance
	Print of horizontal surfaces	Environmental impact minimization
	Development in height	Existing building renovation applications
	Regulations	

More specifically, here are some final considerations on topics of interest that have not yet been thoroughly explored:

- *Acoustic Performance*

  The co-occurrence keywords network shows "thermal conductivity" in proximity, but it remains marginal compared to other printable material characteristics like mechanical or rheological properties. Thermal characteristics of products and materials play an important role in the research topics of the analyzed dataset. Conversely, there is a lack of in-depth study on the acoustic properties of 3D printed components or structures. Only ten documents in the sample contain keywords related to acoustics. Some studies, for instance, focus on foamed concrete or fiber-reinforced cement paste suitable for 3D printing applications [179,180].
- *Seismic Analysis*

  Although many studies explore structural features (highlighted by terms related to mechanical properties, compressive and flexural strength, durability, etc.), few studies have investigated the seismic behavior and shear strength of printed buildings. Studying seismic performance is crucial to make materials and systems for additive printing practically applicable. The interest of companies is evidenced by recent laboratory shear tests performed by Black Buffalo on small and simplified 3D printed walls [181].
- *Environmental Impact Assessment*

Sustainability is considered in many of the analyzed studies, demonstrating its importance. Moreover, results indicate that this topic relates to various aspects such as environmental impact, circular design, or life cycle assessment. However, a deep investigation focusing specifically on these themes is missing. This implies that research on sustainability has not yet been systematically investigated using widely developed environmental impact assessment methods.

- *Existing Building Renovation*

  A significant portion of the building construction sector focuses on renovating existing buildings. A potential research branch may involve applying additive manufacturing not only to new construction but also to existing buildings. 3D construction printing has shown great potential in many areas, yet it has not been sufficiently explored in this regard. Future investigations could exploit the high customizability of 3D printing to propose new retrofitting techniques.

In summary, this overview of unexplored or unresolved topics may serve as a valuable tool for academics to plan impactful and beneficial future research.

3.5.4. Limits of research methods

The results of the current research must be considered alongside some methodological limitations. Bibliometric analysis involves data sampling constrained by time. This methodological approach means that the analyses may be influenced by temporal trends with lower long-term impact. Therefore, the time range set for database querying has been expanded to obtain a publication trend curve starting from low values and achieving a complete curve.

Unlike scientific research results, information from companies operating in the sector is not always available, as there is less interest in disclosing results (or companies may be bound to maintain corporate secrecy). Despite this, the collected dataset is considered extensive enough to support the presented reflections.

3.6. Conclusion

This chapter presents a comparison between an in-depth literature review and a market survey in the field of 3D construction printing. This comparison provides a comprehensive overview of how the academic and technical worlds are differently approaching 3D construction printing, examining both gaps and potentials from environmental, structural, and functional perspectives.

Firstly, the research focuses on a parallel comparison between academic research and the construction market through two dedicated sections. One section details the development of 3D printing technology in academic research, emphasizing temporal and spatial information. Another section surveys all 3D printed buildings developed to date and examines the current companies involved in 3D printed building production.

Secondly, the paper discusses the results, offering a comprehensive overview of 3D construction printing, outlining a roadmap of stages and future directions for the technology, and concluding by highlighting current limitations and unresolved scientific questions.

In total, over 1,800 scientific works in the field of 3D construction printing were analyzed, with the data used to create suitable charts, maps, and trend diagrams. Additionally, in the construction market, more than 80 3D printed structures were identified, and 71 companies were examined.

Compared to previous literature reviews, this research offers a novel critical analysis of the technological evolution and existing gaps, highlighting the shortcomings of current technologies from both scientific and technical viewpoints.

The findings indicate that the main limitations of 3D printed buildings include their reduced size, structural performance, the printing of horizontal surfaces such as slabs, and the difficulty of incorporating reinforcements directly during the printing process. Moreover, despite the widespread application of 3D printed buildings by companies, numerous open research questions persist in the academic sphere. The review reveals a significant lack of scientific knowledge regarding the actual performance, durability, sustainability, life cycle environmental impact, and circular design of these structures.

This review could be a starting point for future research to bridge the gap between existing knowledge and the rapid spread of this technology.

4. AN INTEGRATED METHODOLOGY FOR SUPPORTING THE DESIGN OF 3D PRINTED BUILDING COMPONENTS

4.1. Introduction

The current dissertation has highlighted the evolution of 3D construction printing; the benefits the industry would gain from its use; and the potential that has not been fully explored. The examination prompted the issue of how 3D printing can be a competitive construction technique compared with the widespread techniques. An answer to this debate might be to make the final construction products competitive, or even superior, in terms of performance. This consideration led to formulating the research question **RQ4**: how can 3D printed building components meet multi-objective performance?

In general, additive manufacturing for building envelope elements enables the creation of designs with high geometric flexibility and adaptability [15]. These features are particularly useful for exploring free-form shapes and optimizing component geometries[16]. As noted, 3D printing technology enhances architectural flexibility and shape efficiency by depositing material only where necessary, thus minimizing material usage [14,186,187]. Additionally, the extensive customization options provided by 3D printing are closely linked to the energy efficiency of building envelopes. Building energy consumption is significantly influenced by the envelope's performance, as it governs energy exchanges between the indoor and outdoor environment, such as daylight, heat, and air [188]. By considering material properties and geometric features, the thermal behavior of envelope components can be analyzed using the finite element method (FEM) [189].

A sustainable approach to construction can be achieved by optimizing the performance of building envelopes, which reduces energy consumption during building operation, while simultaneously optimizing the materials used. However, this requires a high degree of customization to tailor the design to specific boundary conditions.

In this context, the design and optimization process can be efficiently supported by parametric 3D modeling. This approach involves CAD where the 3D model is defined by specific design features and constraints. Unlike conventional modeling methods, parametrization allows designers to automate repetitive modifications or make significant changes without needing to rebuild the component from scratch [190]. Consequently, parametric 3D design offers improved and easier control over the model's characteristics throughout the design phases [191]. The ability to create a dynamic model provides two key advantages: the optimization of shapes within the design-analysis workflow and the adjustment of parameters to suit different project contexts.

Additionally, there is a direct relationship between the design of envelope components and their production. Typically, the prefabrication market offers a limited range of variants for the same envelope solution. In this regard, combining parametric design with 3D construction printing as the production technology offers convenient customization tools to enhance performance based on specific boundary conditions.

Consequently, a methodological approach based on parametric design supported by an iterative performance analysis to obtain building envelope components adaptable to different boundary conditions and prefabricated by 3D printing technology has been developed. The application of this process leads to the optimization of simulated performances. The novelty of the presented research concerns the introduction of an iterative process (based on parametric modelling and performance analysis) in combination with the advantages of a 3D printed prefabricated component. Its effectiveness is attributed to the possibility of modifying the parameters of the component (with high geometrical freedom) in order to improve its performance while leaving the printability of the model unchanged. The methodological approach can be adopted to evaluate different aspects of building engineering design by relating multiple simulation systems (energy, acoustic, structural, environmental impact, life cycle, etc.) and related targets to be satisfied. The methodology would provide support to the design choices for the component considering the combinations of different parameters and the limitations imposed by production technology. In particular, the current thesis applies the methodology to different case studies to implement thermal performances of 3D printable envelope components.

4.2. Methodology

The proposed methodology follows an iterative process consisting of four steps to develop a 3D printed component with optimized performance:

I) concept development and parametric modeling;

II) definition of target performance criteria and boundary conditions;

III) performance simulation and parameter identification;

IV) production with 3D printing.

Specifically, the first three steps are repeated until the model's parameters are refined to achieve optimal performance under the specified boundary conditions. Fig. 15 illustrates the four-step methodology.

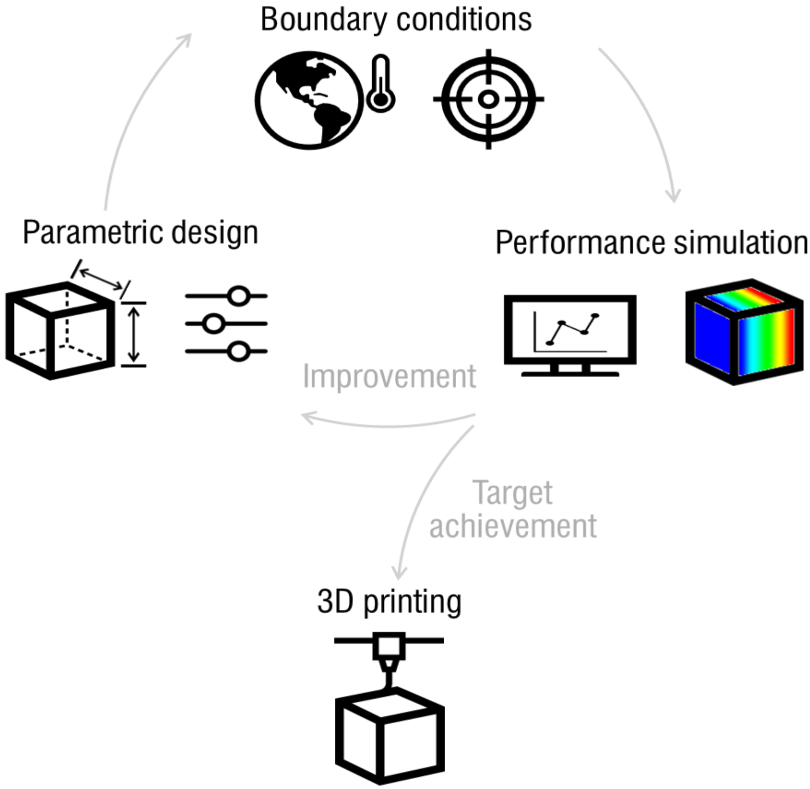


Fig. 15 - Methodology for supporting the design of 3D printed building components.

4.2.1. Concept and Parametric Modelling of a 3D printed Envelope

The design of a 3D printed building envelope begins with identifying the various functions, integration of building systems, and the required performance in terms of e.g. thermal insulation and structural stability. Special emphasis is placed on ensuring dry assembly, modularity, and adaptability, which are critical to the environmental sustainability of the component. Additionally, the design must consider the limitations of current technologies in fabricating complex geometry. Some design parameters will depend on the printing process itself, as features such as layer thickness or curvature can be influenced by the capabilities of the 3D printer and the material being used. In this context, the parametric model offers flexibility for the production phase by linking the different stages of the construction process.

Once the general form of the 3D printed envelope is established, a parametric model is developed using CAD with visual scripting. This step is crucial, as it ensures the flexibility and adaptability of the component for different case studies and boundary conditions. Firstly, parametrizing the external shape allows the component to be adapted and assembled in various contexts. Secondly, the parametrization of specific geometric features (e.g., insulation thickness) facilitates performance optimization for different environments.

4.2.2. Definition of Target Performances and Boundary Conditions

Following the creation of the parametric model, the second step focuses on defining the component's application and its boundary conditions, such as external climate factors or the required indoor environment. This step is crucial as it directly influences the design's purpose. Two key types of information must be identified:

- relevant data for the upcoming performance analysis,
- the expected performance levels necessary to meet minimum regulatory requirements and ensure user comfort.

4.2.3. Simulation and Parameter Adjustment

The third step involves conducting a simulation to evaluate the performance to enhance. In this case, a numerical simulation of the performance of the 3D printed envelope using the FEM is suggested. FEM is a numerical technique applicable to a wide range of engineering problems, including thermal analysis, stress testing, and dynamic analysis. In this methodology, FEM is integrated with parametric modeling in an iterative process to finalize key parameters. The goal is to adjust the model parameters, such as insulation thickness, to meet both regulatory standards and user comfort requirements (regarding thermal performance).

The model's key dimensions are adjusted, and the FEM analysis is repeated until the target performance is achieved and the ideal geometrical dimensions are determined. This process is made more efficient by the parametric model, which allows quick and easy modification of all relevant parameters that affect the component's performance. If the key parameters are not immediately evident, it is advisable to parametrize as many geometric features as possible to facilitate the efficiency process.

5. APPLICATION 1: Design of an efficient 3D printed envelope supported by parametric modelling

5.1. Introduction

The current application is presented in the paper "Design of an efficient 3D printed envelope supported by parametric modelling" published by the present writer [192]. The work represents the first application and then the first phase of the development of the methodology presented in the previous chapter. The case study concerns the design of an envelope component supported by parametric modelling and prefabricated with 3D printing (**RQ5**). In particular, the proposed design process is supported by the parametric 3D design that can interoperate with a performance analysis in order to identify the best components configuration to operate in a specific external environment condition (**RQ6**).

5.2. Methodology

The proposed iterative steps are applied to a building envelope to create high-performing 3D printable components:

I) concept development and parametric modeling;
II) definition of target performance criteria and boundary conditions;
III) performance simulation and parameter identification;
IV) production with 3D printing.

5.3. Case study

The case study involves a prefabricated building envelope produced using 3D printing technology. Previous research has already explored the benefits of this technology, such as reusability, recyclability, modularity, versatility, and adaptability [193]. However, parametric modeling and finite element analysis had not yet been used to enhance the geometric and performance characteristics of the components. In this research, the performance of the building envelope is improved through the proposed approach, ensuring that the modular elements can be assembled using the designed spigot and socket joints.

5.3.1. Parametric Model of the 3D printed Envelope

The parametric 3D model was developed using Grasshopper, a visual algorithm editor integrated with Rhinoceros, a 3D CAD software. Starting from a series of points, curves, surfaces, and eventually volumes were created by connecting the outputs of components to the inputs of subsequent ones. Using number sliders, variable parameters such as the length of the half-lap joints, corner curvature, boundary thickness, spigot and socket joint thickness, and the adjustable filling pattern of the air cavity and insulation panel thickness were defined.

The following steps outline the modeling process using specific components in Grasshopper (Fig. 16).

I) The geometry was first created by defining a set of points representing the corners of the model. Using points as input data allows complete control over the model via the algorithm. The points were connected to the "Move Away From" component, and the half-lap joints were created with adjustable length using a number slider.

II) The outline in the XY plane was formed by connecting the points with the PolyLine component, linked to Curve. Sharp corners were rounded with the Fillet component using an adjustable number slider. The boundary thickness, generated with Offset Curve, was similarly adjustable. The boundary surface was created using the Region Difference and Boundary Surfaces components based on the defined curves.

III) The spigot and socket joints were modeled by starting with the inner curve and offsetting it to create an adjustable thickness. The corresponding surface was generated and then duplicated at the top of the block using the Offset Surface component.

IV) The model includes an air cavity that can be filled with various textures to generate smaller air cells, improving thermal performance. The honeycomb-shaped surface was created using the Hexagon Cells component, with adjustable cell size and boundary thickness using number sliders. The filling texture can be activated or deactivated as needed.

V) The insulation panel was modeled by defining two additional points at a variable distance using "Move Away From" and following a similar procedure to the one in steps I and II.

VI) The final step in generating the 3D model involved extruding the surfaces along a vector on the Z-axis with a specified height. The solids were then subtracted or combined to form two final elements: the envelope block and the insulation panel.

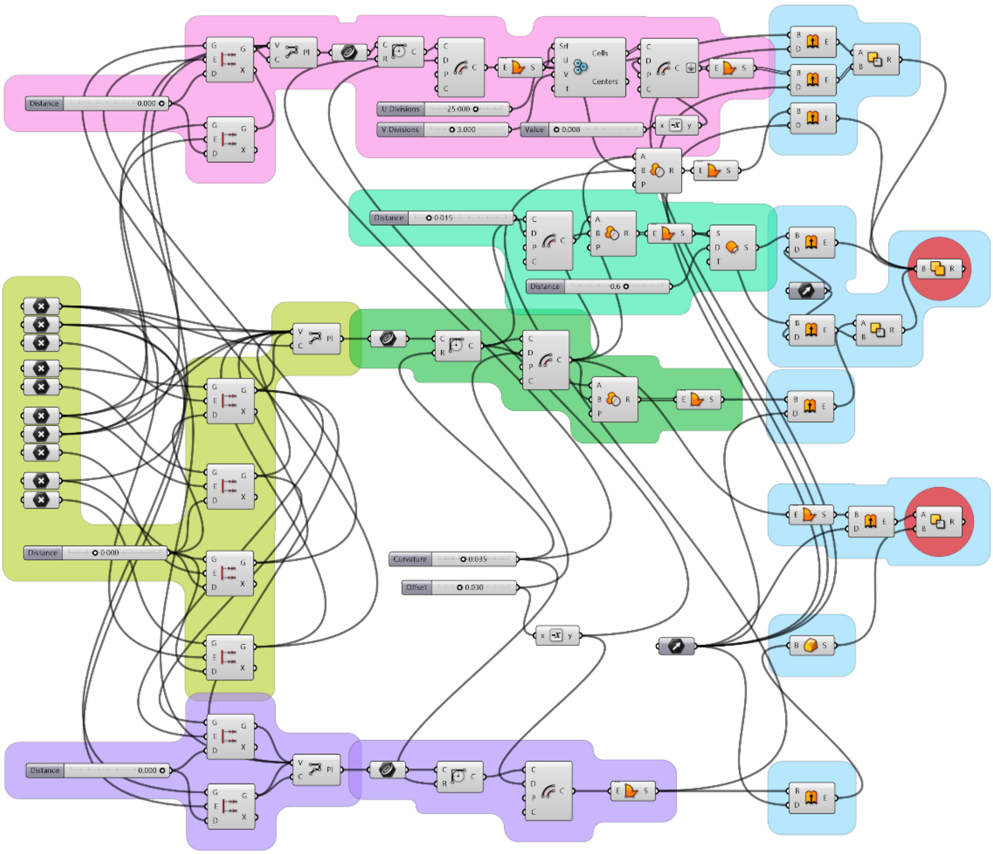


Fig. 16 - Grasshopper algorithm. From geometrical points to volumes. The colored groups refer to the described steps: I) points (yellow); II) boundary surface (green); III) spigot and socket joint surface (light

green); IV) honeycomb-shaped surface (pink); V) insulating panel surface (purple); VI) extruded volumes (blue) and the final two solids circled in red.

The starting configuration (Model A) of the element (as shown in Fig. 17) has the following specifications: total length of 140 cm, half-lap joints 20 cm in length, visible side length of 120 cm, height of 60 cm, block depth of 40 cm, boundary thickness of 3 cm, and insulation panel thickness of 14 cm. Based on this initial configuration, the iterative process was applied to improve performance by adjusting parameters in the visual script. The results section will present the improved models derived from Model A through this process.

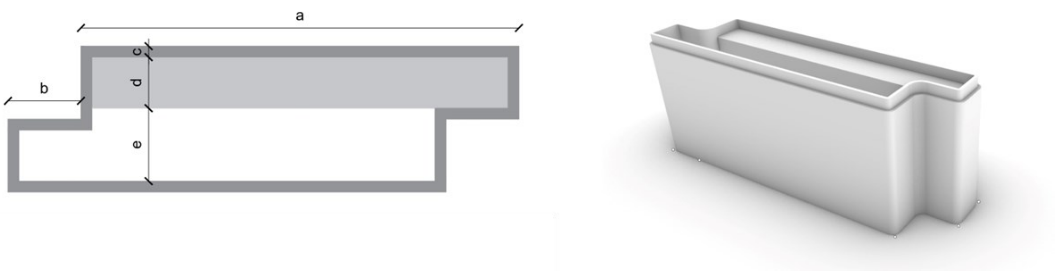


Fig. 17 - Starting configuration: model A.

5.3.2. Definition of Target Performances

According to the Italian Ministerial Decree (DM) No. 162 of June 26, 2015, the thermal transmittance (U-value) of external walls must remain below specific limits, varying across different climatic zones, from the warmest zone A to the coldest zone F zone [194]. This regulation has been used as a reference for setting the required performance targets. The adopted approach allows for the identification of multiple design solutions, with the ability to quickly modify the 3D model based on the desired performance. Specifically, solutions were developed for climate zone C, where the Apulia region is located, as well as for the more severe climate zone F.

5.3.3. Thermal Analysis with FEM Simulation

The thermal analysis is conducted using FEM simulations in ANSYS R22 software to assess heat transfer and heat flux performance. The heat transfer analysis of a building envelope evaluates the temperature transferred from the interior surface (where the indoor environment is warmer) to the exterior surface (which is cooler in winter). Additionally, heat flux analysis estimates the thermal pathways through various thermal bridges, helping to understand how heat is distributed and whether it is emitted or absorbed by different surfaces.

This thermal analysis can be performed for individual components or combinations of components. Specifically, the analysis of combined elements allows for the evaluation of the thermal behavior at half-lap joints between the blocks. By conducting this analysis, model parameters can be adjusted to minimize discontinuities in thermal insulation and reduce the risk of thermal bridges. The two other vertical joints of the block were treated as adiabatic boundaries, due to the symmetrical heat exchange on both sides. This means that each point along the thermal path will have the same temperature in both elements. The same approach was applied to the vertical connections in the FEM model.

Material properties were defined and assigned to the respective volumes in the model. Considering the thermal resistance of air, the empty sections of the blocks were modeled as solid elements with air properties, following methods used in previous thermal studies [195]. Temperature loads were applied to the surfaces of the blocks based on the defined internal and external temperatures, with the internal surface set at 21°C and the external surface at 20°C to evaluate a unitary temperature variation. For all the analyzed models, the external surface was defined as the side adjacent to the insulation panel. The thermal conductivity of Magnesium Potassium Phosphate Cement (MKPC) is 0.7 W/(m K), and that of the insulating material (rock wool) is 0.04 W/(m K). The thermal resistance of a 14 cm or 20 cm air layer is 0.21 (m^2 K)/W, and that of a 6 cm air void is 0.23 (m^2 K)/W. The thermal resistance of air cavities was calculated based on the EN ISO 6946 standard, which outlines different methods for determining the thermal resistance of air layers and voids [196].

5.4. Results: identification of the best parameters

This section presents the results of the proposed iterative process, which optimized parameters to meet the required performance standards for different Italian climate zones. The initial analysis of the model (Model A) showed a thermal transmittance value below the acceptable limit, making it unsuitable for any climate zone. The first improvement strategy involved increasing the thickness of the insulation from 14 cm to 20 cm. While this modification improved overall performance, it was still insufficient (Model B). The second strategy extended the half-lap joints to lengthen the thermal path formed by the concrete, which has lower thermal resistance (Model C). This adjustment reduced horizontal heat flux below the limits for climate zones A and B, making Model C suitable for these contexts.

By combining both strategies, Model D achieved a thermal transmittance suitable for climate zone C. However, the element's empty area exhibited low thermal resistance, which could be further improved by adjusting the internal geometry. Specifically, filling the space with small air cells increased the thermal resistance effect between air layers. A honeycomb-shaped pattern was introduced to fill the cavities within the components, improving thermal performance. This final modification resulted in Model F, which meets the transmittance requirements for climate zone F.

Fig. 18 illustrates the models analyzed, and Tab. 6 provides a detailed description of the models, highlighting the parameter adjustments made to the original Model A. Tab. 7 summarizes the heat flux results for each model. The first column shows the heat flux across the entire envelope, while the second column focuses on the heat flux through a vertical plane perpendicular to the internal and external surfaces, located at the center of the element. These heat fluxes were calculated based on a unitary temperature difference, allowing a comparison of the average heat flux and the thermal transmittance for each building envelope type, including the effect of thermal bridges at the joints.

Fig. 19 illustrates the results of the simulated temperature field and heat flow for Model D, which has a 14 cm air cavity. The temperature distribution is nearly uniform and varies linearly in the direction of the heat flow from the exterior to the interior (as shown in the upper part of the figure). The heat flux distribution chart highlights the thermal bridge formed by the joint between elements, where energy is concentrated (indicated by the red area in the central part of the figure). This area shows a heat path of lower resistance due to the change in material with higher thermal conductivity.

Tab. 6 Geometrical parameters of the analysed models.

Model	**Thotal length** **a** [m]	**Half-lap joint lenght** **b** [m]	**Boundary thickness** **c** [m]	**Insulation thickness** **d** [m]	**Air cavity** **e** [m]
A	1.20	0.20	0.03	0.14	Cavity of 0.14 m
B	1.20	0.20	0.03	0.20	Cavity of 0.14 m
C	1.40	0.40	0.03	0.14	Cavity of 0.14 m
D	1.40	0.40	0.03	0.20	Cavity of 0.14 m
E	1.40	0.40	0.03	0.14	Cells of 0.06 m
F	1.40	0.40	0.03	0.19	Cells of 0.06 m

Tab. 7 Resulting Heat Fluxes of each model and satisfaction of the thermal transmittance limits of every Italian climatic zone.

Model	**Average Heat Flux** [W/(m² K)]	**Average Heat Flux of middle surface (without thermal bridge)** [W/(m² K)]	**Climatic zone limit satisfaction** [W/(m² K)]
A	**0.4362**	0.2378	
B	**0.3891**	0.1674	A-B (<0.40)
C	**0.3758**	0.2343	A-B (<0.40)
D	**0.3534**	0.1667	C (<0.36)
E	**0.3044**	0.2153	D (<0.32)
F	**0.2525**	0.1620	F (<0.26)

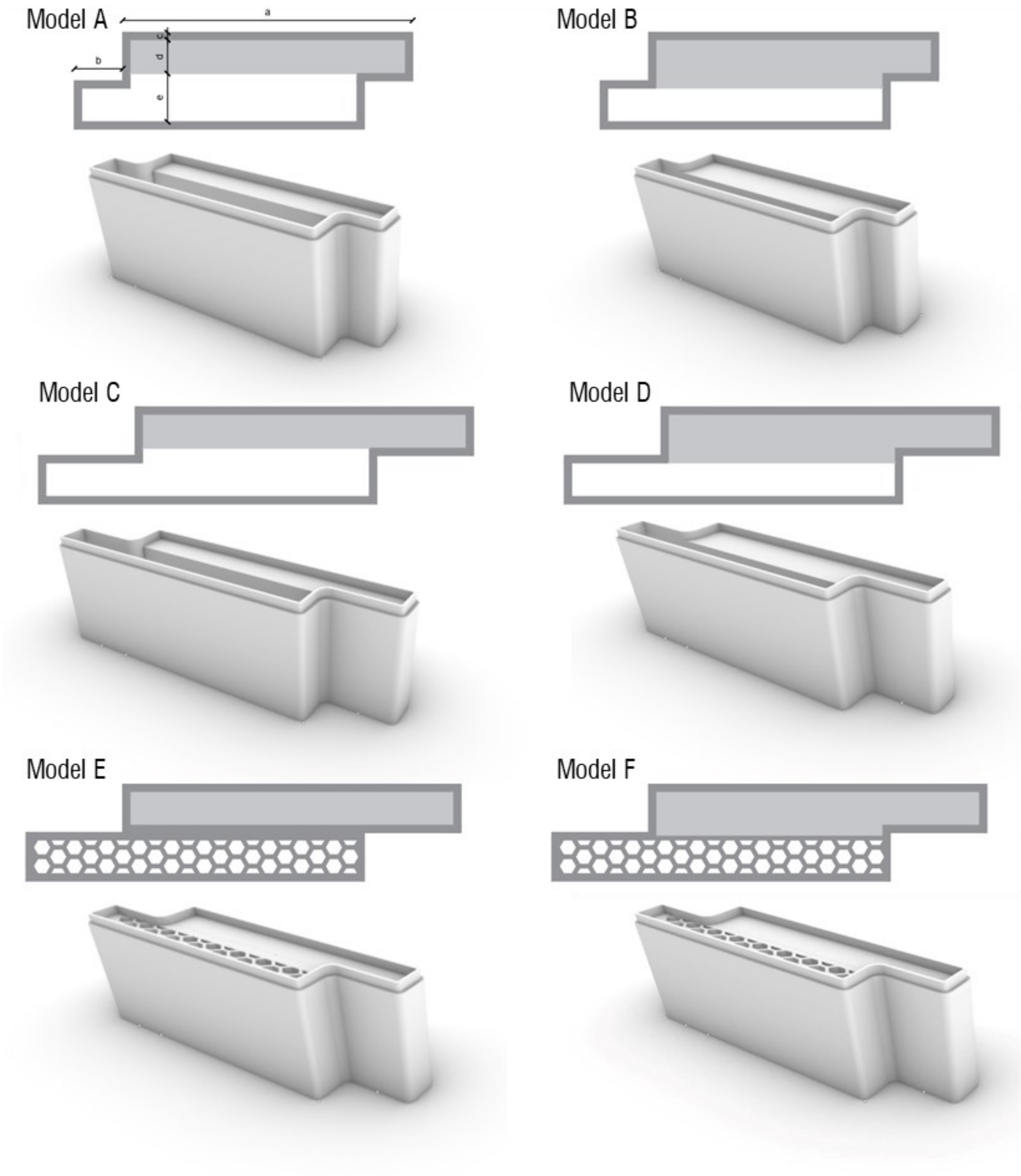
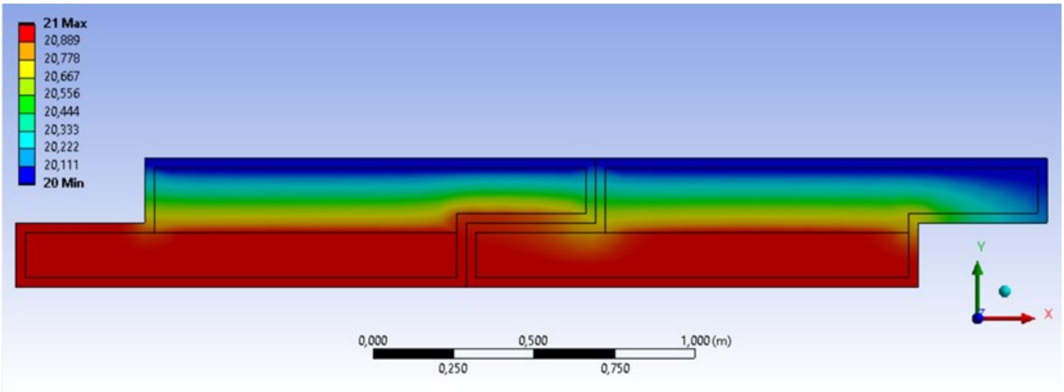
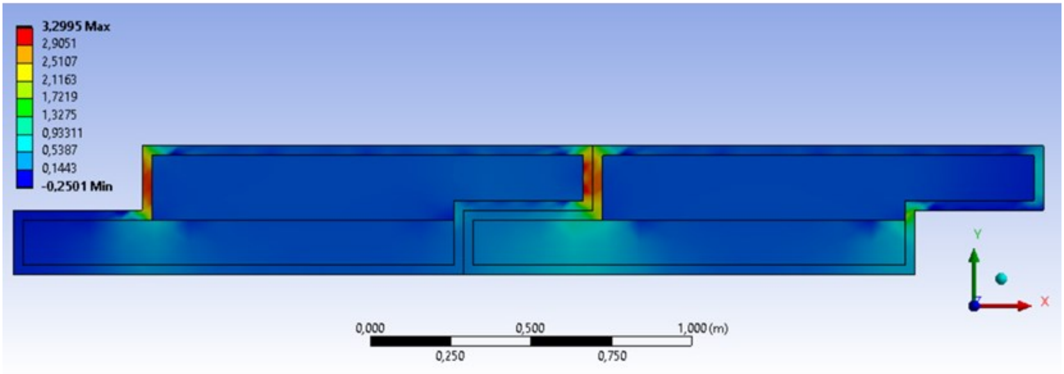


Fig. 18 - Representation of the different models: total length (a); half-lap joint length (b); insulation thickness (d); air cavity (e).

Model D: Temperature distribution



Model D: Heat flux



Model D: Vecor diagram of Heat flux

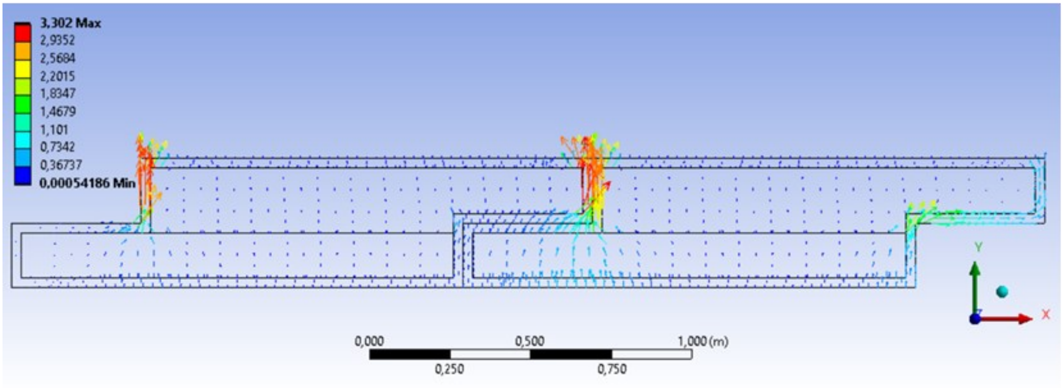


Fig. 19 - Thermal analysis results of model D. Upper part: temperature distribution. Central part: heat flux. Lower part: vector diagram of heat flux.

5.5. Conclusion

3D construction printing offers unprecedented flexibility and customization in building products. In this context, the present chapter introduces a first application of the iterative process aimed at achieving an effective parametric design, supported by thermal performance analysis, to identify the optimal component configuration for specific external environmental conditions. Specifically, this procedure is applied to the design of an efficient 3D printed building envelope component, adjusting its configuration (geometry, insulation thickness, and interlocking) based on the requirements of various Italian climate zones.

The novelty of this research lies in applying the proposed iterative process, which combines parametric modeling and performance analysis, to the development of a 3D printed prefabricated component. The iterative approach, coupled with the flexibility and customizability of 3D printing, provides significant advantages during the design phase. The component parameters can be adjusted to improve performance without the need for complete re-modeling, while maintaining printability. Additionally, parametric design enables the evaluation of the impact of individual parameters on thermal performance by simply altering one variable at a time.

Moreover, the proposed iterative methodology allows for the generation of multiple configurations, enabling the simultaneous analysis of a variety of design solutions. This approach prevents unnecessary performance maximization where it is not needed, thus conserving materials. In conclusion, the iterative design process results in five different configurations of the 3D printed envelope, each tailored to meet the regulatory requirements of the different Italian climate zones.

6. APPLICATION 2: Material re-use in 3D printed building components

6.1. Introduction

The application of the current chapter ties in with the previous application by integrating the methodology with a materials recycling approach. In particular, a preliminary step, dealing with the reuse design that is also connected to the choice of printing materials, is added to the method. Furthermore, in this scenario, the parameterization is not only related to geometric characteristics but also to the thermal characteristics of the materials that may affect the final result. The subsequent two case studies have been illustrated in two dedicated articles by the present writer [197,198].

In recent decades, the scientific and technical communities have been confronting the critical issues of waste generation and energy demand in building and infrastructure development. One of the goals of Agenda 2030 is responsible consumption and production, which emphasizes reducing waste through prevention, reduction, recycling, and reuse [199]. Traditional construction methods generate a substantial amount of waste, and both construction and demolition processes require significant resource consumption. The rising costs of raw materials, both economically and environmentally, are impacting the sustainability of building construction on a broad scale. Yilong et al. identified the high demand for concrete as a major contributor to CO_2 emissions and, consequently, to the unsustainability of construction [200]. As a result, upgrading the construction industry through innovative processes has become essential. New technologies and more efficient resource management, particularly focusing on material reuse and recycling, represent the fundamental innovations needed in the construction sector.

The potential of additive manufacturing has been discussed extensively in previous chapters. Another aspect to be mentioned is the effectiveness of this technology if used with recycled materials, which are often incorporated into 3D printable mixtures [201].

Despite its promise, 3D printing faces certain challenges, especially in achieving materials that meet the necessary printing requirements, such as suitable rheology, extrudability, and buildability. To meet these standards, many of the current 3D printing mixtures still rely on Portland cement and fine aggregates, which are energy-intensive to produce and contribute significantly to CO_2 emissions [202].

Various 3D printing mixtures have been studied to include recycled materials, but few focus on using predominantly recycled mixtures. Pozzolanic materials have been used to partially replace cement, offering advantages like high early strength, better workability, lower porosity, and corrosion resistance. Some studies have explored using by-products as additives in cement mixtures. For example, silica fume is a by-product of silicon and ferrosilicon alloy production [203,204], fly ash is a by-product of coal combustion in thermal power plants [205–208], and rice husk ash comes from agricultural waste [209]. Other researchers have investigated replacing natural aggregates with recycled aggregates from construction and demolition waste [210–212]. Additionally, the use of recycled sand in concrete 3D printing has shown potential for reducing costs and environmental impact, though it remains in its early stages [213]. Promising substitutes for aggregates in sustainable 3D printing include recycled brick aggregate [214], glass cullets [215], and natural fibers [216].

Recycled materials can also be applied effectively in thermal insulation for traditional buildings. Plastics and glass, for instance, have been widely used to create recycled insulation panels or filler materials [217]. This "reuse" approach could also be applied to the insulation of 3D printed building blocks. Fine-grained or loose materials could be integrated directly into 3D printed blocks during the printing process, a task that automation in construction will further streamline.

To summarize, while recycled materials for 3D printing have been extensively studied, few examples in the literature involve components made entirely from sustainable recycled materials. Moreover, existing methodologies often overlook the synergy between parametric design and performance simulations to refine the geometry of 3D printed components.

The present chapter introduces a preliminary step to the methodological approach for designing efficient 3D printed building envelopes incorporating reused materials in the printing mixture and insulation filler. The process begins with defining the reuse design by selecting materials for recovery, followed by parametric modeling and simulation to optimize the block's shape, and finally, identifying the best settings for 3D printing production in a specific boundary condition. This approach is applied to two different case studies using a mortar with recycled glass or rubber for the printing mixture and glass fiber or cellulose for the insulation layer. The model of the first case study has been already presented in the previous chapter, while the model of the second case study consists of blocks with an interlocking honeycomb-inspired shape.

6.2. Methodology

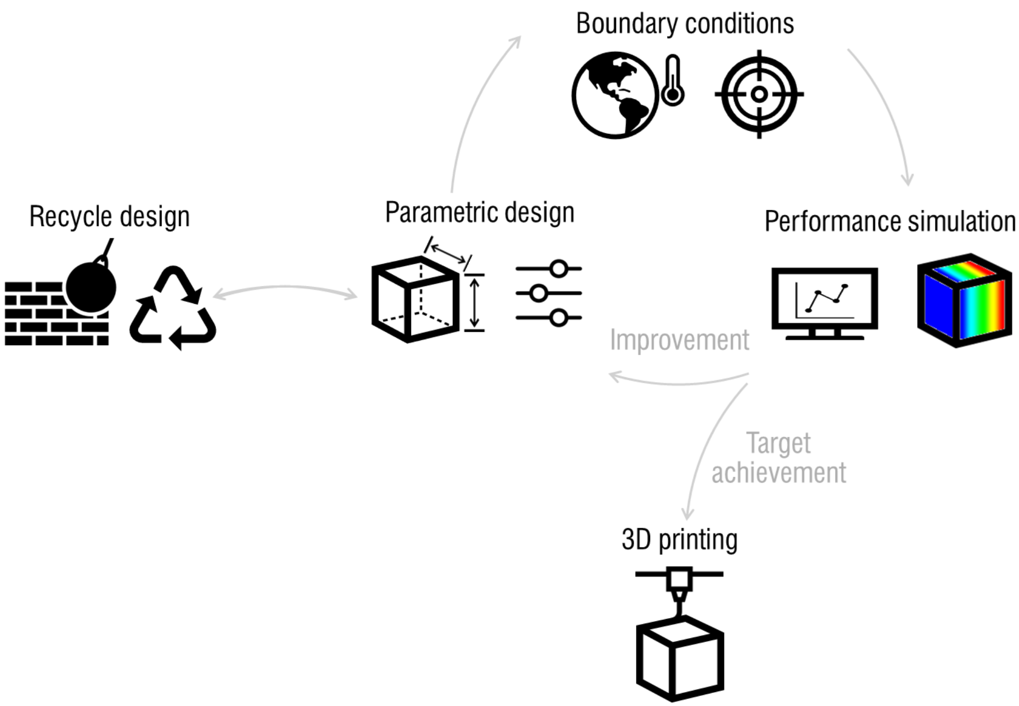


Fig. 20 - Overview of the proposed methodology

The proposed methodology is based on five steps (Fig. 20) from the use of recycled materials to the creation of 3D printed building components:

I) recycle strategies design;
II) concept development and parametric modeling;
III) definition of target performance criteria and boundary conditions;
IV) performance simulation and parameter identification;
V) production with 3D printing.

6.2.1. Recycle strategies design

The initial phase of the methodology focuses on developing a reuse strategy. Construction and demolition waste account for a significant portion of global waste production. This type of waste is well-suited for reuse or recycling into secondary raw materials due to its large volume and low toxicity. During the reuse strategy phase, techniques for intervention or demolition are defined, and a list of potentially reusable components and recyclable materials is established. Typically, recyclable fractions of construction and demolition waste include stone, ceramics, glass, wood, and metals. Reuse strategies for such materials may involve incorporating recycled aggregates into concrete mixes or transforming waste into thermal insulating materials [218,219].

Next, the feasibility of integrating material from the identified demolition waste into 3D printable materials can be explored. This depends on the rheological properties that the printed material must meet, which have been investigated in previous studies. According to Roussel et al., the following conditions should be satisfied:

- the initial yield stress must exceed gh_0, where g is gravitational acceleration.
- the yield stress in the bottom layer must be greater than $\rho gH/\sqrt{3}$, where ρ is the material's density.
- the initial shear elastic modulus should be higher than $\rho gh_0/e_{tol}$, where e_{tol} is the tolerable deformation of the layer.
- the Young's elastic modulus must be greater than $3\rho gH^3/2\delta^2$[220].

Another possibility is to consider incorporating waste materials with thermal properties into the printed components. This can be achieved by adding insulating material either directly into the printing mix or as a filler. The insulating filler can be inserted either during or after the printing process, depending on the complexity of the internal geometry and the type of filler. For simple geometries, loose insulating materials can be added after the component is fully printed. However, for more complex geometries, the print process can be paused after several layers to properly insert the insulating material, filling the voids as needed. Currently, this operation is performed manually, but it could be automated in the future using collaborative robots in construction.

6.2.2. Parametric Modelling

Before proceeding with parametric modelling, the conceptual design of the component must be clearly defined. This includes specifying the required functions, integrating building services, and addressing performance requirements in terms of thermal protection and structural integrity. Additionally, the conceptual design must consider the current technological limitations in producing complex geometric shapes [221].

Once the conceptual design is established, parametric modelling can begin. This approach uses mathematical equations managed through visual scripting to construct geometry. It allows for the immediate modification of the model's shape by adjusting the values of certain parameterized dimensions. Therefore, after finalizing the conceptual design, all dimensions that need to be parameterized, such as thickness, lengths, heights, and internal fills, must be identified. The parameterization of specific geometric characteristics, such as insulation thickness, is essential for optimizing the component's performance during the later simulation and iteration phases.

6.2.3. Target Performance Definition

The desired performance of the component is determined by its intended function, boundary conditions, and usage. Based on these factors, target performance levels can be established to meet both the minimum regulatory standards and user comfort requirements.

6.2.4. Iterative Simulation

The iterative simulation phase allows for the adjustment of model parameters. FEM analysis, combined with parametric modelling, is used to evaluate performance and iteratively adjust specific geometric parameters to meet the target performance. In this approach, FEM and parametric modelling work together through an iterative process, aiming to find the optimal parameters that satisfy regulatory standards and user comfort regarding thermal behavior.

6.2.5. 3D Printing Setup

In the 3D printing phase, an important step involves enhancing printability and potentially optimizing the extrusion path. Achieving consistent product quality requires converting the component shapes into a continuous extrusion path. However, complex geometries may not always allow for continuous 3D printing. In such cases, it becomes necessary to customize the slicing and g-code to ensure accurate printing with minimal errors, such as reducing overlap in the extrusion path [222].

6.3. Case study 1: application to a prefabricated 3D printed envelope

The case study focuses on applying the proposed methodology to a 3D printed building envelope. This prefabricated envelope component, employed as case study in section 5.1, is designed to be used as external cladding in both new constructions and building renovations, with the flexibility to adapt to various climatic zones. The current paragraph aims to enhance the performance and sustainability of this 3D printed building component by incorporating recycled materials.

6.3.1. Recycle design

The recycle strategy in this case study focuses on utilizing recycled materials as aggregates for the cementitious printing mixture, along with recycled insulating materials. The cementitious materials being examined consist of MKPC, incorporating either recycled glass or rubber as aggregates. These innovative cement-based mortars were introduced in a previous study [223]. MKPC is composed of Magnesium Oxide (MgO), Potassium Dihydrogen Phosphate (KDP), borax, fly ash (FA), silica fume (SF), and water. The study considers two printing mixtures: MKPC with recycled expanded glass (0.5–1 mm) and MKPC with rubber granules (0.5–1 mm) from tire casings.

Expanded glass is produced from a type of glass that cannot be recycled within the glass manufacturing industry. Although glass can be effectively recycled without quality loss, not all glass waste can be reused for this purpose [224]. In contrast, rubber, especially from tires, presents challenges in disposal due to the slow decomposition of polymeric materials. However, tire rubber can be repurposed into powders of various sizes, which can then be categorized and reused in different applications, such as in the production of sustainable concrete or mortars using rubber granules as aggregates [224,225].

Lightweight aggregate-based mortars also enhance the thermal insulation performance of printed elements. Both types of MKPC mixtures have been experimentally tested to evaluate their thermal properties. The tests were conducted on cylindrical samples (10 cm in diameter and 5 cm in height) using the ISOMET 2104 device (Applied Precision Ltd., Bratislava, Slovakia). This device measured thermal behavior by applying a constant heat flow through a heating probe on the sample surface and recording temperature changes over time. The experimental temperature data was compared with the analytical solution of the heat conduction equation to derive the results. Tab. 8 presents key thermal characteristics: thermal conductivity (λ, W/mK), thermal diffusivity (α, m^2/s), specific heat (cp, J/kgK), and average temperature (tm, °C).

For the thermal analysis simulation, input data for the two printing mixtures were as follows: MKPC with expanded glass has a density of 950 kg/m^3 and a thermal conductivity of 0.16 W/mK, while MKPC with tire rubber granules has a density of 1120 kg/m^3 and a thermal conductivity of 0.20 W/mK.

Another approach to glass recycling involves producing glass fibers for use in glass wool insulation panels or loose-fill insulation [226]. In the case study, this material was selected for thermal insulation because, depending on the internal geometry of the printed element, glass fiber insulation can either be inserted or blown into place. Additionally, a multi-criteria sustainability assessment shows that recycled glass is one of the most favorable insulation materials across various scenarios [227]. Based on a review of the literature, the following properties of glass wool were used in the thermal simulation analyses: density of 160 kg/m^3 and thermal conductivity of 0.05 W/(mK) [228].

Tab. 8 Thermal characteristics of MKPC sample containing recycled expanded glass (MKPCglass) and MKPC sample containing tyre rubber granulate (MKPCrubber).

	Conductivity λ [W/mK]	**Diffusivity a** [m^2/s]	**Specific heat cp** [J/kgK]	**Temperature t_m** [°C]
$MKPC_{glass}$	0.16	0.46	1.07	32.05
$MKPC_{rubber}$	0.20	0.17	1.18	32.52

6.3.2. Model parameters definition

The model considered as case study has been described in chapter 5. The proposed building envelope has been previously studied for its benefits such as reusability, recyclability, modularity, versatility, and adaptability [222]. Specifically, the editable parameters of the 3D model created using Grasshopper were the total length, the half-lap joint length, the external shell thickness, the insulation thickness and the optional adjustable filling pattern. Fig. 21 displays the 3D printable building envelope model with the parameterized dimensions.

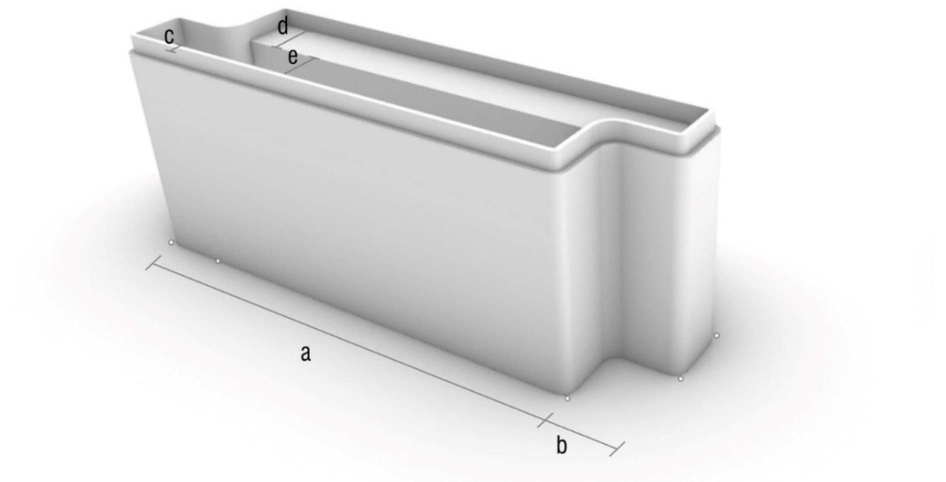


Fig. 21 - Parameters: **a** total length; **b** half-lap joint length; **c** external shell thickness; **d** insulation thickness; **e** air cavity.

6.3.3. Target performance

The target performance is based on specific boundary conditions. The chosen location is the Apulian region of Italy, which, according to Italian Ministerial Decree (DM) No. 162 of June 26, 2015, falls under climate zone C. For different climate zones, external walls must comply with a maximum thermal transmittance value as outlined in the regulations. This thermal transmittance limit has been set as the target performance for the case study. Therefore, the goal of the thermal analysis, along with the variation of geometrical and material parameters, is to achieve a thermal transmittance of 0.34 W/m^2K or less.

6.3.4. Simulation and iterations

The previously modeled element was analyzed with respect to the boundary conditions and the specified recycled materials. In particular, by conducting repeated thermal analyses and adjusting the variable parameters, the configuration that most closely matches the target thermal transmittance for the case study area was achieved. Each configuration was examined by using either MKPC with recycled expanded glass or MKPC with tire rubber granulate as the 3D printing mixture.

6.3.5. Results

A total number of 12 models have been analyzed: 6 considering $MKPC_{glass}$ and 6 considering $MKPC_{rubber}$ as printing material (Tab. 9).

Tab. 9 Models with related variation parameters and relative thermal transmittance results.

Models	Parameters						**Results**
	Printing material	a [m]	b [m]	c [m]	d [m]	e [m]	**Thermal transmittance [W/m^2K]**
A	$MKPC_{glass}$	1.20	0.20	0.03	0.14	0.14 m	0.249
B	$MKPC_{glass}$	1.20	0.20	0.03	0.20	0.14 m	0.209
C	$MKPC_{glass}$	1.40	0.40	0.03	0.14	0.14 m	0.219

D	$MKPC_{glass}$	1.40	0.40	0.03	0.20	0.14 m Cells	0.195
E	$MKPC_{glass}$	1.40	0.40	0.03	0.14	0.06 m Cells	0.201
F	$MKPC_{glass}$	1.40	0.40	0.03	0.19	0.06 m	0.167
G	$MKPC_{rubber}$	1.20	0.20	0.03	0.14	0.14 m	0.272
H	$MKPC_{rubber}$	1.20	0.20	0.03	0.20	0.14 m	0.230
I	$MKPC_{rubber}$	1.40	0.40	0.03	0.14	0.14 m	0.239
L	$MKPC_{rubber}$	1.40	0.40	0.03	0.20	0.14 m Cells	0.205
M	$MKPC_{rubber}$	1.40	0.40	0.03	0.14	0.06 m	0.219
N	$MKPC_{rubber}$	1.40	0.40	0.03	0.19	Cells of 0.06 m	0.179

Finally, for both material types, the optimized configuration was identified. The models, along with their respective thermal properties, were compared.

The following results were obtained:

- using MKPC with recycled expanded glass, a thermal transmittance value of 0.249 W/m^2K is achieved by model A;
- using MKPC with tire rubber granulate, a thermal transmittance value of 0.272 W/m^2K is achieved by model G.

Both configurations meet the climatic zone C limit of 0.34 W/m^2K. Fig. 22 shows an example (Model A) of the analysis carried out with the FEM software Ansys.

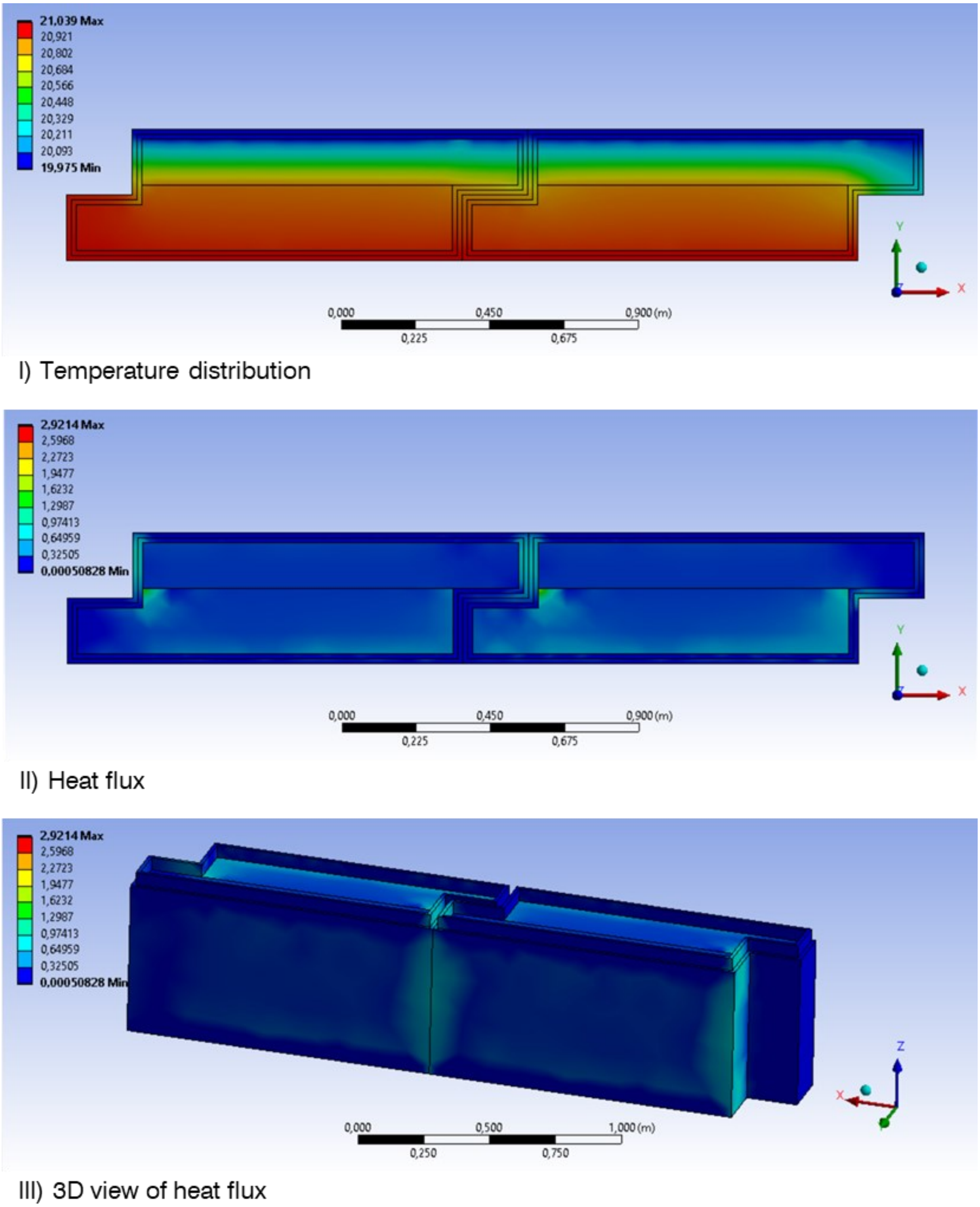


Fig. 22 - Thermal analysis results of model A using MKPC with recycled expanded glass. I) temperature distribution; II) heat flux; III) 3D view of heat flux.

6.4. Case study 2: application to 3D printable honeycombs-shaped blocks

The case study focuses on applying the proposed methodology to the design of an envelope system made up of modular 3D printable components. The structure follows a hexagonal pattern, which is easily manufacturable using 3D printing technology. The geometry of these elements enables both interlocking and the filling of the hexagonal cells with insulating material, enhancing thermal performance. Building on this concept, the aim is to adjust the geometric and material parameters to optimize thermal efficiency according to the specific requirements of a given climate.

6.4.1. Recycle design

The current case study shares the same recycling strategies of 6.3 section considering MKPC with expanded glass or MKPC with tire rubber granules as printable material. The input data of the thermal analysis simulation for the two printing mixtures were the following.

- $MKPC_{glass}$: density=950 kg/m^3, thermal conductivity=0.16 W/mK;
- $MKPC_{rubber}$: density=1120 kg/m^3, thermal conductivity=0.20 W/mK.

The hexagonal cells were filled with cellulose insulation, a loose material that can be easily blown in after 3D printing. This material's sustainability comes from its production using recycled paper. From a thermal perspective, cellulose is an excellent insulator due to its low density (around 40 kg/m^3), with an estimated thermal conductivity of 0.04 W/mK [229]. These parameters were used as input data for the thermal analysis simulation.

6.4.2. Model parameters definition

As outlined, the design concept focuses on creating an external envelope element based on a hexagonal pattern. The specific features of this element can vary depending on factors such as the climate zone or the building's intended use. Therefore, at this stage, the methodology includes not only the design and modeling of the component but also the definition of variable parameters. In this research, the variable geometric parameters include the number of hexagonal cells (with a total block thickness ranging from 21 to 26 cm), the size of the hexagonal cells, and the wall thickness. However, the block height (20 cm) and width (40 cm) remain constant. The materials used for 3D printing also serve as a variable parameter (affecting thermal conductivity) for future thermal analyses, while the insulating material remains constant. Fig. 23 illustrates the 3D model's dimensions of the printable block with honeycomb geometry, highlighting which are fixed and which are parameterized.

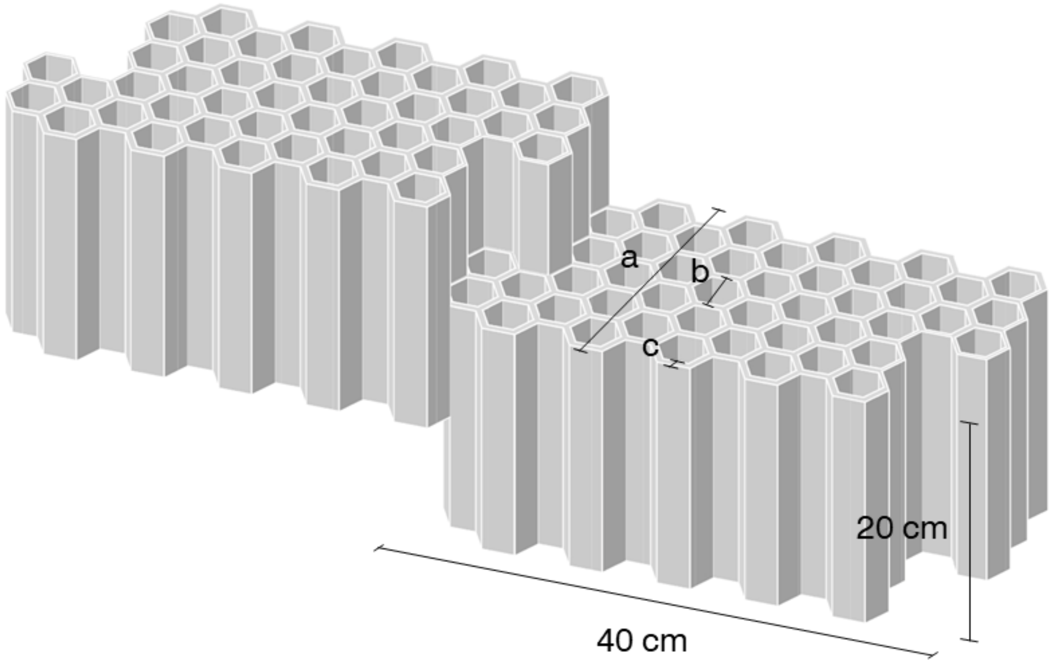


Fig. 23 - 3D printable block with honeycomb geometry and possible assembly system. The dimensions show constant and variable geometrical parameters of the 3D printable envelope block: (a) number of hexagonal cells; (b) hexagonal cell size; (c) wall thickness.

6.4.3. Target performance

Once again, the performance requirement is to achieve a thermal transmittance of less than 0.34 W/m²K (corresponding to the Italian climatic zone C).

6.4.4. Simulation and iterations

The thermal analysis was conducted using ANSYS R22 software as a steady-state thermal analysis. The simulation assesses heat transfer between a surface at a higher temperature and one at a lower temperature. For each 3D model, the inner surface was set at 20°C, and the outer surface at 0°C. The other surfaces, which have symmetrical heat exchange due to contact with adjacent elements, were treated as adiabatic boundaries. Each material was defined and assigned to the relevant volume. The simulation produced results on temperature variation along the heat path, total heat flux, and directional heat flux along the axis perpendicular to the surfaces with different temperatures. By dividing the heat flux by the temperature gradient, the thermal transmittance of the element was calculated.

6.4.5. Results and discussion

A total of twenty-four different models were analyzed to meet the required performance by varying the parameters. Tab. 10 lists the analyzed models along with the corresponding parameter variations and summarizes the results: heat fluxes and their respective thermal transmittance values.

Tab. 10 Models with related variation parameters and results (heat fluxes and the relative thermal transmittance).

Models	**Parameters**				**Results**	
	Printing material	Hexagon Number	Hexagon size [mm]	Wall thickness [mm]	**Heat flux [W/m²]**	**Thermal transmittance [W/m²K]**
A	$MKPC_{glass}$	5	45	5	5.64	0.28
B	$MKPC_{rubber}$	5	45	5	6.71	0.34
C	$MKPC_{glass}$	5	40	10	5.48	0.27
D	$MKPC_{rubber}$	5	40	10	6.49	0.32
E	$MKPC_{glass}$	6	35	5	6.34	0.32

F	$MKPC_{rubber}$	6	35	5	7.55	0.38
G	$MKPC_{glass}$	6	30	10	6.15	0.31
H	$MKPC_{rubber}$	6	30	10	8.15	0.41
I	$MKPC_{glass}$	7	28.3	5	5.97	0.30
J	$MKPC_{rubber}$	7	28.3	5	7.02	0.35
K	$MKPC_{glass}$	7	23.3	10	6.37	0.32
L	$MKPC_{rubber}$	7	23.3	10	7.54	0.38
M	$MKPC_{glass}$	4	45	5	6.95	0.35
N	$MKPC_{rubber}$	4	45	5	8.26	0.41
O	$MKPC_{glass}$	4	40	10	6.72	0.34
P	$MKPC_{rubber}$	4	40	10	7.96	0.40
Q	$MKPC_{glass}$	5	35	5	7.56	0.38
R	$MKPC_{rubber}$	5	35	5	9.01	0.45
S	$MKPC_{glass}$	5	30	10	7.28	0.36
T	$MKPC_{rubber}$	5	30	10	8.63	0.43
U	$MKPC_{glass}$	6	28.3	5	6.92	0.35
V	$MKPC_{rubber}$	6	28.3	5	7.29	0.36
W	$MKPC_{glass}$	6	23.3	10	7.03	0.35
X	$MKPC_{rubber}$	6	23.3	10	8.26	0.41

The overall thermal transmittance decreases as cell size increases, which is due to the larger volume of insulating material with lower thermal conductivity. As expected, even with a reduction in the material layer's thickness, the thermal performance improves slightly. The internal honeycomb cell structure extends the heat path from the inner surface at a higher temperature to the outer surface at a lower temperature. The temperature distribution (Fig. 24.I) shows a nearly linear variation along the heat flux direction, while the heat flux distribution (Fig. 24.II) highlights areas of lower thermal resistance, corresponding to the differing materials and their respective conductivities.

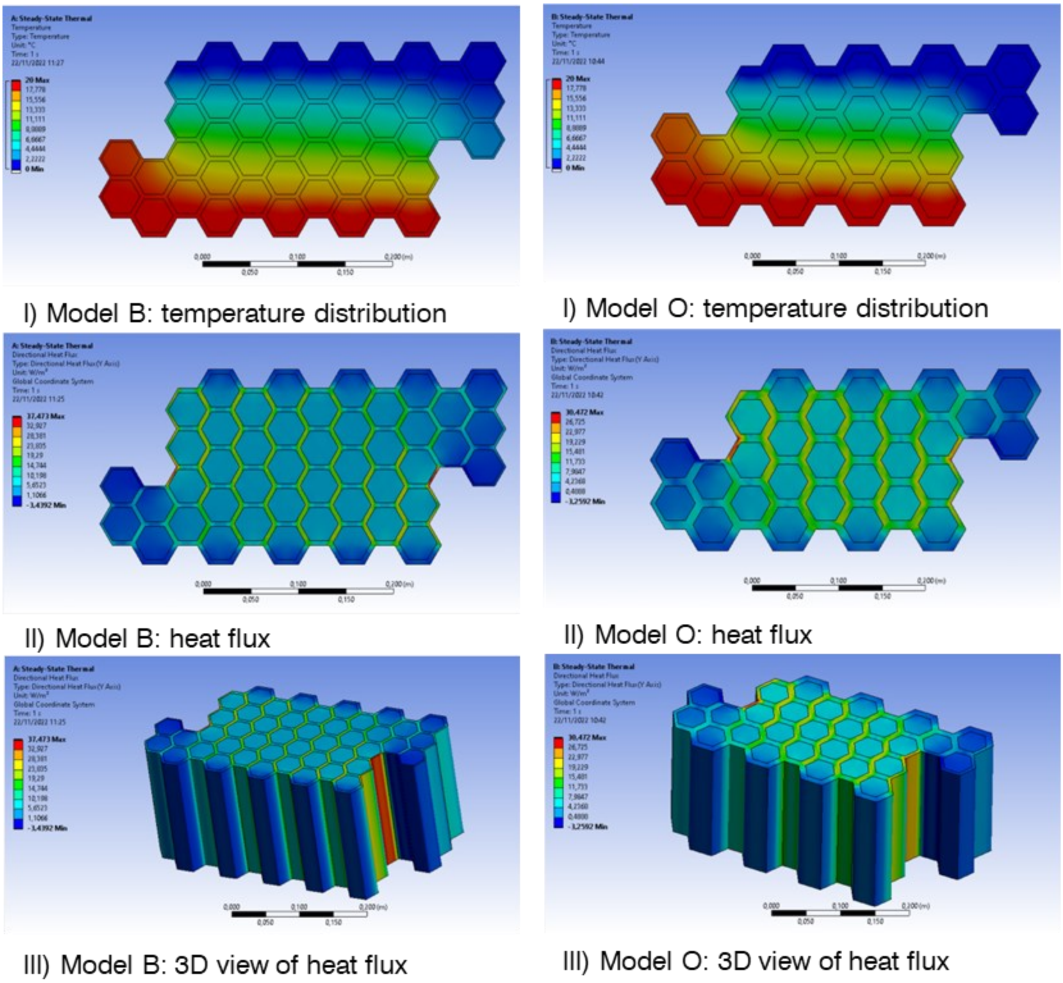


Fig. 24 - Thermal analysis results of model B and O: I) temperature distribution; II) heat flux; III) 3D view of heat flux.

A multilinear regression analysis was conducted to estimate the relationship between the independent variables and thermal transmittance. The resulting equation for the model is presented below.

$$y = 0.719 - 0.056\, x_1 - 7.644\, x_2 - 6.931\, x_3 + 1.435\, x_4$$

- y = thermal transmittance;
- x_1 = hexagon number;
- x_2 = hexagon dimension;
- x_3 = wall thickness;

- x_4 = printing material conductivity.

Although the models have varying parameters, the influence of the insulating layer thickness, one of the most significant factors, on the analysis results is evident. Fig. 25 illustrates the correlation between thermal transmittance and total insulation thickness, which is determined by the product of the hexagonal cell size and the number of hexagonal cells. Each point in the graph represents a model with a different parametric configuration. The series of points show how transmittance changes as insulation thickness increases, while the printing material (and thus its conductivity) and wall thickness remain constant. Linear trendlines for the four series are shown, and it is evident that all have the same slope. As wall thickness decreases, the trendline shifts horizontally, as thinner walls create more space for insulation. When the conductivity of the printing material changes, the trendline shifts vertically.

The results show that models B and O, which contain rubber and glass aggregates respectively, have thermal transmittance values closest to the target value of 0.34 W/m^2K. Therefore, these configurations can be applied to form the external block wall for the climate zone in the case study. In fact, when combined with finishing elements to smooth the external and internal surfaces, the overall thermal transmittance of the entire envelope can be considered below the required limit.

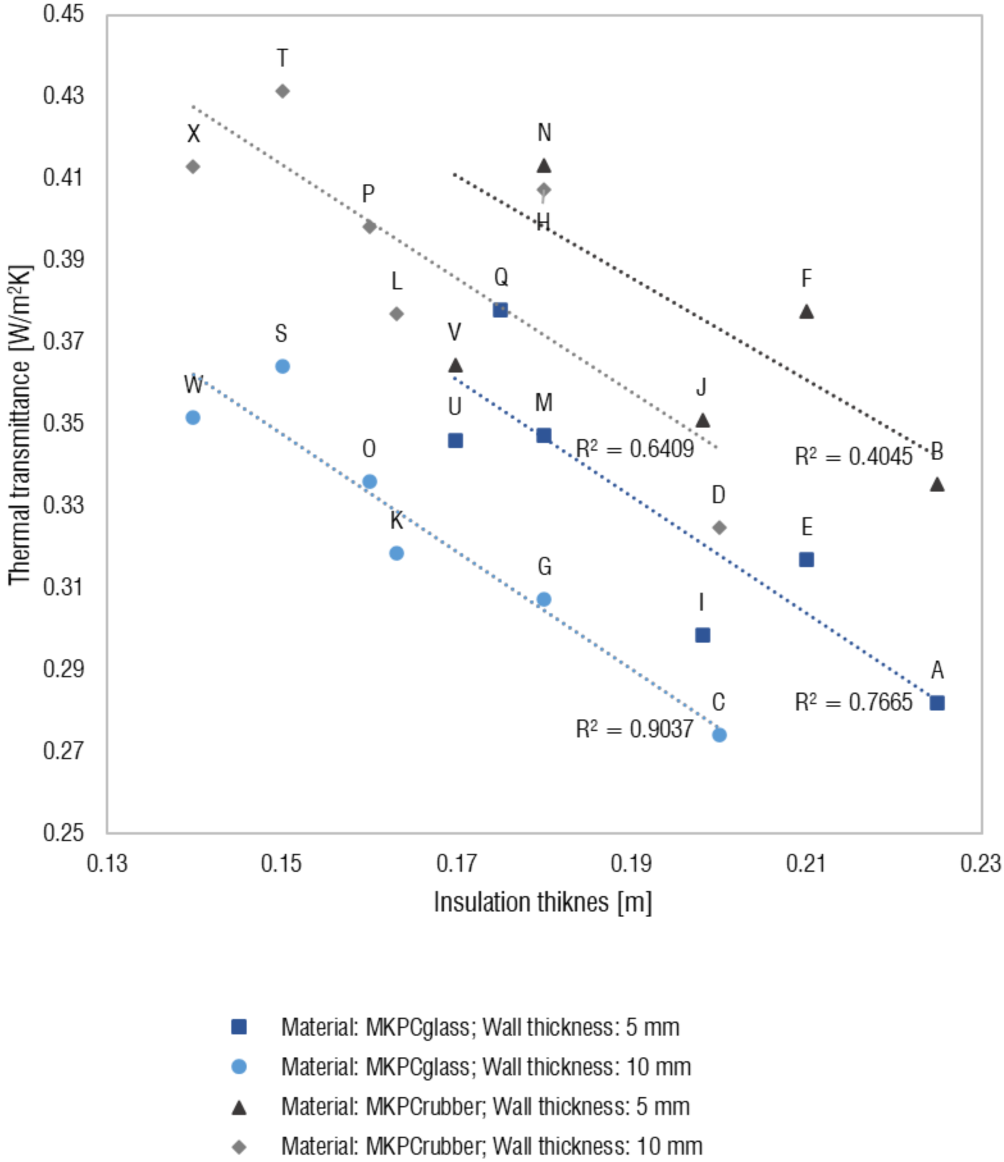


Fig. 25 - Linear regression of the Relationship between thermal transmittance and total insulation thickness of four model types.

6.4.6. 3D printing prototype test

To verify the printability of the proposed shape, a prototype was produced in the laboratories of the Polytechnic of Bari. The model was scaled down and prototyped during a printing test (Fig. 26) using clay as the printing material. Specifically, the model was reproduced at a 1:10 scale using a Delta Wasp 40100 printer in the "FabLab Poliba" at the Polytechnic of Bari. The 3D printed prototype confirmed the feasibility of the designed geometry. The extrusion process did not encounter common printing errors, and the printed shape was achieved without deformation, accurately reflecting the digital 3D model.

Fig. 26 - 3D Printing prototype test conducted in the FabLab Poliba of the Polytechnic of Bari.

6.5. Conclusion

3D construction printing represents a promising technology for integrating recycled materials with innovative geometries. This chapter proposes a methodology for designing building components with high performance that can be 3D printed using reused materials. The methodology was applied to two case studies involving a building envelope system and a block with a honeycomb geometry. Through this approach, both elements were thermally optimized by adjusting geometric and material parameters based on specified boundary conditions. Two different 3D printing admixtures were evaluated, both using cement-based materials (MKPC) with recycled aggregates made from expanded glass or rubber granulate from tires. The thermal properties of these lightweight mortars were assessed through experimental testing. Glass fibers material was assumed as insulating filler for the first case study. Cellulose insulation was suggested as a filling material for the hexagonal cells of the second case study. The parametric models were analyzed using FEM simulations, demonstrating the potential of combining 3D printing technology with recycled materials. In fact, one configuration for each printing admixture for each case study reached the thermal transmittance limit for the selected climate zone. Future research would focus on combining structural and thermal performance, automating simulations, and optimizing parameters iteratively to develop an effective design system for 3D printed components using recycled materials.

7. APPLICATION 3: Life cycle assessment of building envelopes manufactured through different 3D printing technologies

7.1. Introduction

This chapter is dedicated to the implementation of the basic methodology with the analysis of environmental impacts in the step concerning performance simulation to answer **RQ7** concerning the actual sustainability of 3D printed building products. Considering the expected environmental impacts of a specific building product can then be a criterion for the preference of a particular design over the same thermal performance for instance. Conducting a Life Cycle Assessment (LCA) may lead to a preference for one type of 3D printing over another. The chapter has as its main reference a work published in a dedicated journal paper [230].

The introduction of 3D printing into the construction industry has had a transformative effect, opening up new possibilities for the Architecture, Engineering, and Construction (AEC) sector. This shift has driven significant investments in 3D printing technologies, both in Europe and globally [19].

For these technologies to establish themselves in the construction market, they must perform competitively and be sustainable. Although many studies focus on maximizing the performance of various 3D printing technologies, few directly compare their sustainability. Some technologies have been tested in building component production [231], with the most promising methods being large-scale monolithic 3D printing in situ, prefabrication of 3D printed components, and the Fused Deposition Modeling (FDM) based formwork technique [232,233]. These methods employ large gantry cranes, small gantry cranes, and FDM 3D printers, respectively, and their applications in construction include bridges, houses, offices, and other structures [234].

Given the growing focus on environmental concerns, the sustainability of concrete 3D printing is essential for broader industry adoption. Consequently, several studies have assessed the environmental impacts of these innovative processes, determining whether they are more eco-friendly than traditional methods [235]. LCA is the most widely used method for comparing the carbon footprints of traditional casting and 3D construction printing (3DCP) [236]. Concrete production is typically the largest contributor to the environmental impact of both traditional and 3D printed structures, accounting for up to 97% of total effects [237]. Thus, efforts to make raw materials more sustainable are ongoing, though challenging [238]. However, 3D printing offers benefits in terms of geometric complexity and optimized material use, which can reduce the environmental impact [239].

Most studies on 3DCP focus on evaluating extrusion-based technologies (such as large-scale and prefabrication methods and comparing them with traditional casting [240,241]. The sustainable potential of large-scale 3D printing compared to conventional construction has been demonstrated [242]. Other studies highlighted the importance of raw materials in the thermal performance and sustainability of 3DCP [243]. As geometric complexity increases, 3D printed structures become more sustainable than traditional methods using formwork [244]. The use of simple geometry 3D printed formwork for concrete casting can improve the sustainability [245].

Despite growing interest and expanding research, several aspects of 3D printing sustainability in construction remain underexplored. Few studies examine the impact of geometric configurations and infill patterns on the sustainability of 3D printed structures. No study has fully considered how geometric complexity and 3D printing affect thermal properties and sustainability. Additionally, sustainability comparisons between different printing technologies are rare, and newer techniques, such as the "Eggshell" method, have not been thoroughly investigated from an environmental perspective.

The study illustrated in the current chapter addresses these gaps by assessing the environmental impacts and thermal properties of three printing technologies under development in the construction sector: large gantry cranes, small gantry cranes, and FDM printers. These technologies are applied in monolithic construction, prefabrication, and FDM-based formwork to create concrete building envelope components (**RQ5**). The study investigates various configurations, including different infill complexities and wall thicknesses, through thermal simulations and LCA analyses. This comprehensive approach provides insights into the sustainability of these technologies, highlighting how geometric parameters affect the environmental footprint of structures.

The novelty of this research lies in two key aspects: investigation of how different technologies and techniques can achieve thermally efficient building envelopes using parametric modeling (**RQ6**) and analysis and identifying through LCA the advantages of various 3D printing methods for more sustainable development in the future (**RQ7**).

The next three paragraphs describe the printing technologies whose environmental impact will be assessed in the following case study

7.1.1. Monolithic 3D Printing with a large Gantry System

Monolithic 3D printing occurs directly on-site, where the building envelope is printed as a single, continuous structure. This eliminates the need for assembling multiple components, as each building story is produced in a single printing session. Three primary technologies currently facilitate large-scale monolithic 3DCP: the gantry system, cable-suspended systems, and robotic arms [246]. Among these, the gantry system is the most widely adopted and has gained significant market traction [247]. It uses a frame structure to support the printer's extruder and actuator, allowing it to move along the X, Y, and Z axes [248]. Leading companies like COBOD, Contour Crafting Corporation, and PERI Construction use this system for monolithic construction [246].

7.1.2. 3D Printing Prefabrication with a small Gantry Systems

In 3D printing for prefabrication, the building envelope is produced as individual components, either on-site or in specialized labs, and later assembled [19,222]. Common machinery for this technique includes gantry-based 3D printers and robotic arms. In contrast to monolithic printing, prefabrication typically uses smaller machines, with print volumes of approximately 3m × 3m × 3m. Many machines on the market have similar energy usage and printing speeds [247].

7.1.3. FDM-Based Formwork

The FDM-based formwork technique is an innovative process that uses FDM 3D printing to create thin, flexible molds for concrete structures, offering more geometric versatility than conventional formwork [233]. Concrete is cast into the 3D printed mold, which can be produced on-demand. While many technologies can create formwork, FDM is particularly well-suited for thin molds [249]. Though still relatively uncommon, this technique has shown potential through research and emerging industrial applications [250].

FDM-based formwork is highly adaptable for both on-site and laboratory production due to the portability of small 3D printers, offering a high degree of design freedom. This flexibility allows for the creation of intricate building envelopes with interlocking components.

7.2. Materials and methodology

The proposed methodology has been implemented for the specific application described in the present chapter (fig. 27). In particular, it follows the iterative process based on the four known steps.

I) *Concept development and parametric modeling*.
II) *Definition of target performance criteria and boundary conditions*. In particular, the target has been defined as a thermal transmittance value to be met by different geometrical configurations and having the least impact on the environment.
III) *Performance simulation and parameter identification*. Specifically, the application involves the simulation of thermal performance and environmental impacts using an LCA analysis. As detailed below, the two simulation models are systematized to achieve the two defined objectives (thermal and sustainability criteria).
IV) *Production with 3D printing*. The adoption of different printing technologies is evaluated as a further implementation of the methodology at this stage.

In particular, the considered technologies are large-scale 3D printing, pre-fabrication 3D printing, and FDM-based formwork.

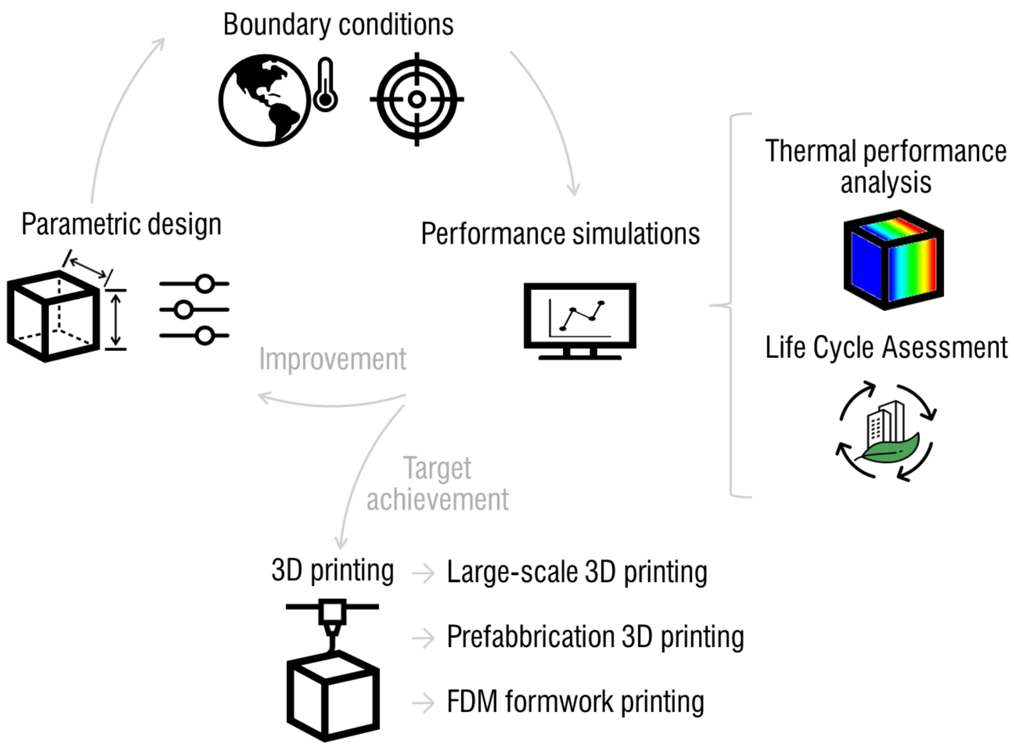


Fig. 27 - The specific implementation of the methodology for application 3.

7.3. Case study

7.3.1. Wall configuration design and parametrization

The case study regards a printable wall consisting of an outer shell filled with a sinusoidal pattern. The chosen internal infill, featuring a sinusoidal geometry, was pre-determined as it is widely regarded as standard practice [251]. This geometry is effective in extending the heat flow path between the wall's inner and outer layers and in preventing wall collapse during the printing process. Additionally, the sinusoidal shape can be easily adapted or left unaltered depending on the printing resolution offered by the production technology.

To facilitate the analysis of different configurations, a parametric model of the component was developed using Rhino and Grasshopper software. By adjusting the number of sinusoids (NS), wall thickness (T), wall length (X), and wall width (Y), the parametric model allows for the generation of all desired configurations. Fig. 28 illustrates the geometric parameters.

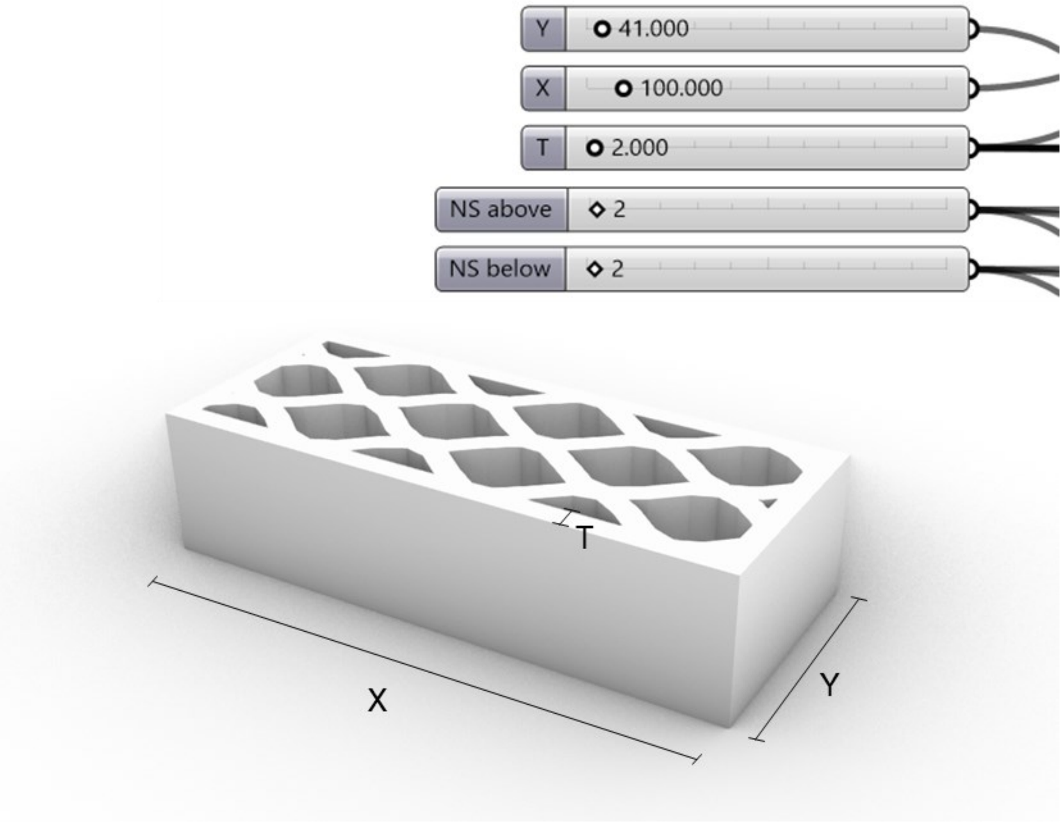


Fig. 28 - Geometrical parameters: NS number of sinusoids, T wall thickness, X length and Y width.

As thermal parameters have been defined constituent materials of the envelope components that are common to all configurations. Specifically, a cementitious mixture with a thermal conductivity of 0.28 W/(mK) has been chosen as the printing material.

In addition, a cellulose fiber-based insulation material with a thermal conductivity of 0.04 W/(mK) has been defined as a cell-filling material.

7.3.2. Target performance

A target thermal transmittance has been established as the performance to be reached by all the configurations varying the geometrical parameters. The target thermal transmittance U value of 0.29 W/(m^{2}K) refers to Italian Ministerial Decree (DM) No. 162 of 26 June 2015 and particularly corresponds to a climatic zone D. The reaching of the same thermal performance would allow the comparison of the different block' configurations from the point of view of environmental impact conducting an LCA concerning the different printing technologies. Therefore, it is possible to define as an additional performance the objective of sustainability.

7.3.3. 3D printing technologies

In order to compare different configurations of a wall with the same thermal performance from the point of view of environmental impacts, it was chosen to compare different types of production based on additive printing. The techniques (illustrated in the introduction paragraph) are based on prominent methods from the literature [232], including: large-scale, in-situ monolithic 3D printing; prefabrication of 3D printed components; and prefabricated 3D printing formwork, referred to as the "Eggshell" technique when produced with ultra-thin shells [233]. As a result, the case study focuses on these three key 3D printing methods in the architecture, engineering, and construction industry. Each technique utilizes different 3D printing technologies, and for the proposed study, large gantry cranes, small gantry cranes, and FDM 3D printers were chosen accordingly.

I) *Large gantry cranes*

COBOD's BOD2 3D printer was chosen for the proposed study, designed for large, in-situ concrete structures [137]. The BOD2 can print structures up to 15 m in width, 15 m in length, and 8 m in height, with a speed of up to 1 m/s and layer thicknesses reaching 300 mm. Operated by a team of 3–4 people, it uses cementitious mixtures blended with superplasticizers to achieve the right fluidity and viscosity for printing without deformation [221]. The printer requires support from additional equipment like the Silo, Mini Batch, and Concrete Piston Pump, all positioned near the construction site. The Silo stores dry cement for producing 3D-printable concrete. At the same time, the Mini Batch is equipped with an agitator mixer and control system to customize concrete mixtures, even utilizing local materials when possible. The Concrete Piston Pump transfers the prepared material from the Mini Batch to the printer's hopper for extrusion.

II) *Small gantry cranes*

The proposed research uses the Be More 3D SMART 2500 gantry-crane printer, capable of achieving thinner layers (up to 60 mm) and speeds of up to 0.150 m/s [113]. This enables greater precision and the creation of complex shapes, though printing times increase when geometry complexity rises. Prefabrication also requires additional machinery like smaller concrete mixers and pumps due to lower material requirements.

III) *FDM 3D printers*

The study employs the Wasp WASP 3 MT HDP printer, with a volume of 1 m × 1 m × 1 m and the ability to print with polylactic acid (PLA) pellets, which can now be sourced as recycled material [115]. The machine produces layers as thin as 1.5 mm, facilitating precise, intricate designs, though production times are considerably longer.

Each technology involves limitations at the level of printing parameters such as the thickness of the extruded layer or the size of the final product. To be consistent in the type of geometry and the type of print to build it, the configurations for each technology are defined based on technological constraints, such as wall thickness and resolution [221].

I) *Large-scale 3D printing*

Monolithic 3D printing typically produces walls with substantial thickness and either no pattern infill or a simple one. As a result, the configurations for this technology feature wall thicknesses of either 6 cm or 10 cm, with either no internal pattern or a single internal sinusoid. Since monolithic printing allows for the direct in-situ construction of long elements, the corresponding configurations are assumed to have a length of 2.5 m.

II) *Prefabrication 3D printing*

Prefabricated concrete components can be printed with thinner walls, so configurations with thicknesses of 4 cm or 6 cm have been defined. Due to the higher precision of this method, it can accommodate up to 4 internal sinusoids. The length of prefabricated elements must be manageable for handling, so a length of 1 m has been set.

III) *FDM-based formwork*

The FDM formwork technique is highly versatile, involving the printing of ultra-thin formwork. This allows for wall thicknesses ranging from 6 cm down to as little as 2 cm. The internal structure can include anywhere from 0 to 6 sinusoids. The length of the elements, considering the smaller dimensions of printers used for this technology, has been set at 0.6 m.

7.3.4. Thermal performance analysis

The various configurations and their production technologies can be compared in terms of environmental impact, assuming equal performance. In this study, an LCA analysis was chosen to evaluate the envelope components with identical thermal transmittance. To achieve this, once the geometric parameters were established, an iterative thermal analysis was conducted, holding the independent variables constant while adjusting the Y parameter to reach the specified thermal transmittance value. In particular, wall sinusoids number NS, wall thickness T and length X represent the independent variables as they have been defined for the different configurations, on the other hand, width Y constitutes the dependent variable as it is supposed to vary during the iterative thermal analysis until the thermal transmittance reaches the defined value.

The thermal analysis has been carried out with the parametric model directly connected to a thermal analysis algorithm using Grasshopper based on Therm software (Fig. 29). Once the geometry to be analyzed is connected, data on geometric areas, materials and relative thermal conductivity are entered into the program. The input data consist of the independent geometric parameters of the different defined configurations while the output data consists of the width Y obtained once the desired thermal transmittance value is achieved. The algorithm employed automates the binding between the parametric model and the thermal model, making iterations and the process of reaching the target smooth and fast.

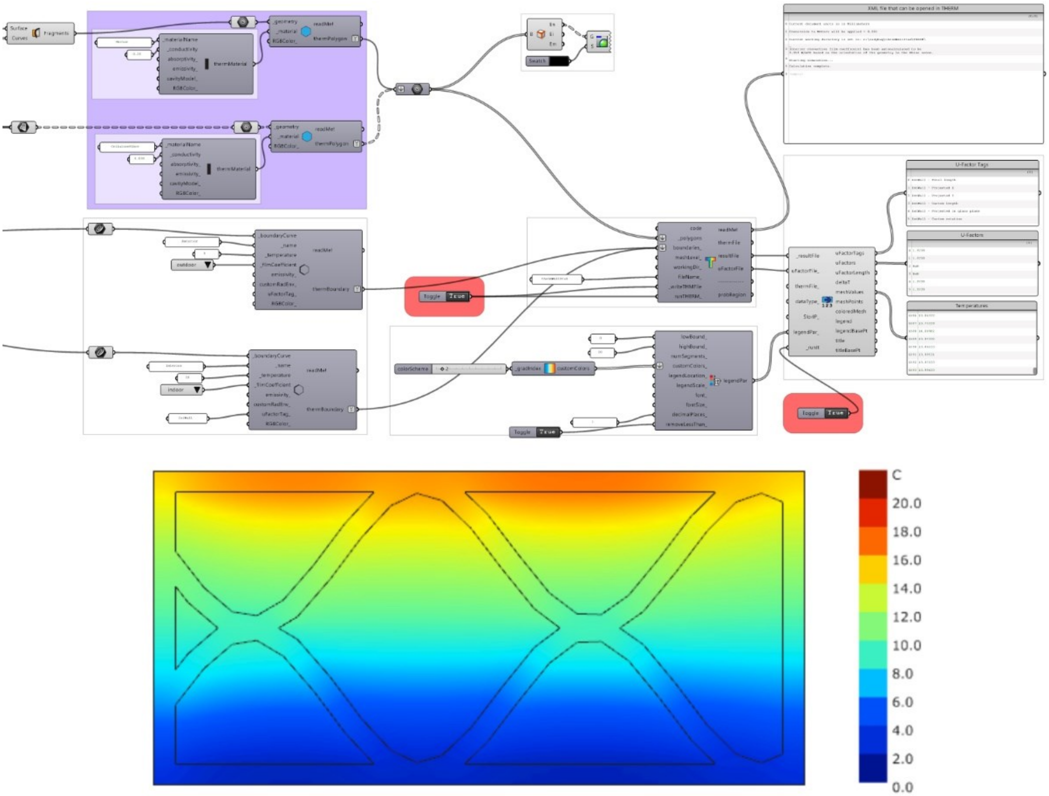


Fig. 29 - Thermal analysis algorithm in Grasshopper based on Therm software.

7.3.5. Life cycle assessment

This section aims to evaluate the environmental impacts of different 3D printing techniques conducting LCA analysis.

Within the sustainability assessment were considered the three different 3D printing technologies: Monolithic 3D printing with a large gantry system (Scenario 1); prefabrication of concrete 3D printing with a small gantry system (Scenario 2); form-work with Fuse Deposition Modelling (Scenario 3).

The unit of comparison is defined as the production of a section of an external wall with an area of 1 m^2 with a thermal transmittance of 0.29 W/m^2K. Using a unitary value ensures uniform thermal performance for the 3D printed walls with the different printing technologies and allows the comparison of the different wall configurations. The attainment of configurations with the same quantified thermal performance, due to the previous thermal analysis, acts as the reference unit for the comparison among different production scenarios.

The presented LCA can be considered as "from cradle to gate" as it includes all phases from the extraction of raw materials to the wall construction phase. In particular, the analysis covers the following key phases:

- raw materials of the cementitious mixture extraction and transport, including additives like superplasticizer and polypropylene (PP) fibers. The same concrete mixture was used in all 3D printing scenarios. For the monolithic 3D printing case, direct transport of materials to the construction site was considered, while in Scenarios 2 and 3, transport to off-site production facilities was assumed;
- PLA pellets production, pelletizing, and transport for the FDM process in Scenario 3;
- insulation material production and transport (cellulose fiber) in all scenarios;
- materials mixing and pumping, accounting for electric energy consumption. Different pump powers were used in each scenario;

- 3D printing process for concrete (Scenarios 1 and 2) and PLA (Scenario 3), including energy and compressed air consumption;
- transport of the monolithic 3D printer, silos, mixer, and pump to the production site in Scenario 1;
- concrete wall transport to the site in Scenarios 2 and 3;
- assembly of prefabricated walls using cranes in Scenarios 2 and 3.

The production phases of machinery were excluded from the analysis, as due to their long lifespan their production would result in negligible [252]. Additionally, the service life and end-of-life of the walls were considered outside the system boundaries, since their environmental impact is mainly related to ambient heating and cooling [253,254]. Given that the functional unit was based on thermal properties, the walls' service life has little effect on the comparative analysis.

The Life Cycle Inventory (LCI) phase utilized primary data from industrial 3D printing processes and secondary data from literature, mathematical models, and the Ecoinvent 3.1 database in SimaPro. Impacts per unit of materials (e.g., kg of concrete or kWh) were calculated and multiplied by the resource use for each configuration. This made it possible to quantify the impacts of the different configurations. The concrete mix used in all scenarios was modeled based on data from partners, consisting mainly of cement, fly ash, micro silica fume, fine aggregates, water, and small amounts of additives like superplasticizers and PP fibers.

Material consumption for concrete and insulation (cellulose fibers) was calculated using the CAD models and the material densities defined during the thermal simulations. In the same way, the volume and thus the weight of the FDM-based formwork used in scenario 3 was calculated considering a 5 mm nozzle. The energy consumption of 3D printers, concrete mixers, and pumps was calculated based on machine flow rates and power data provided by manufacturers, using the average Italian energy mix.

Moreover, compressed air was required for the FDM printer's build plate (scenario 3), and crane energy usage during assembly was included for Scenarios 2 and 3. Transport distances for materials and equipment were estimated using supplier locations and Google Maps, with a 500 km distance assumed for concrete walls in

Scenarios 2 and 3. Transport impacts were based on Ecoinvent database considering Euro 5 freight lorries. No additional transport was required for Scenario 1, where walls were printed on-site.

According to previous studies on the sustainability assessment of concrete structures, two key impact categories were selected to measure the potential environmental effects of the scenarios [255,256].

- Global Warming Potential (GWP), measured in kilograms of CO_2 equivalent (kg CO_2 eq), which quantifies greenhouse gas emissions and their impact on climate change. The methodology of the International Panel on Climate Change (IPCC) was followed.
- Cumulative Energy Demand (CED), measured in megajoules (MJ), which quantifies all direct and indirect energy usage from renewable and non-renewable sources throughout the lifecycle phases.

Special attention was given to the energy consumption of 3D printing technologies compared to traditional methods. The Life Cycle Impact Assessment (LCIA) phase was conducted using SimaPro software with the Ecoinvent database to translate LCI data into potential environmental impacts.

7.4. Results

7.4.1. Thermal analysis results

Fig. 30 provides a comprehensive overview of the defined 3D printed envelope configurations, categorized based on the three different types of printing technologies. As previously mentioned, the length of the elements remains constant for each technology, while the wall thickness and the number of sinusoids is adjusted.

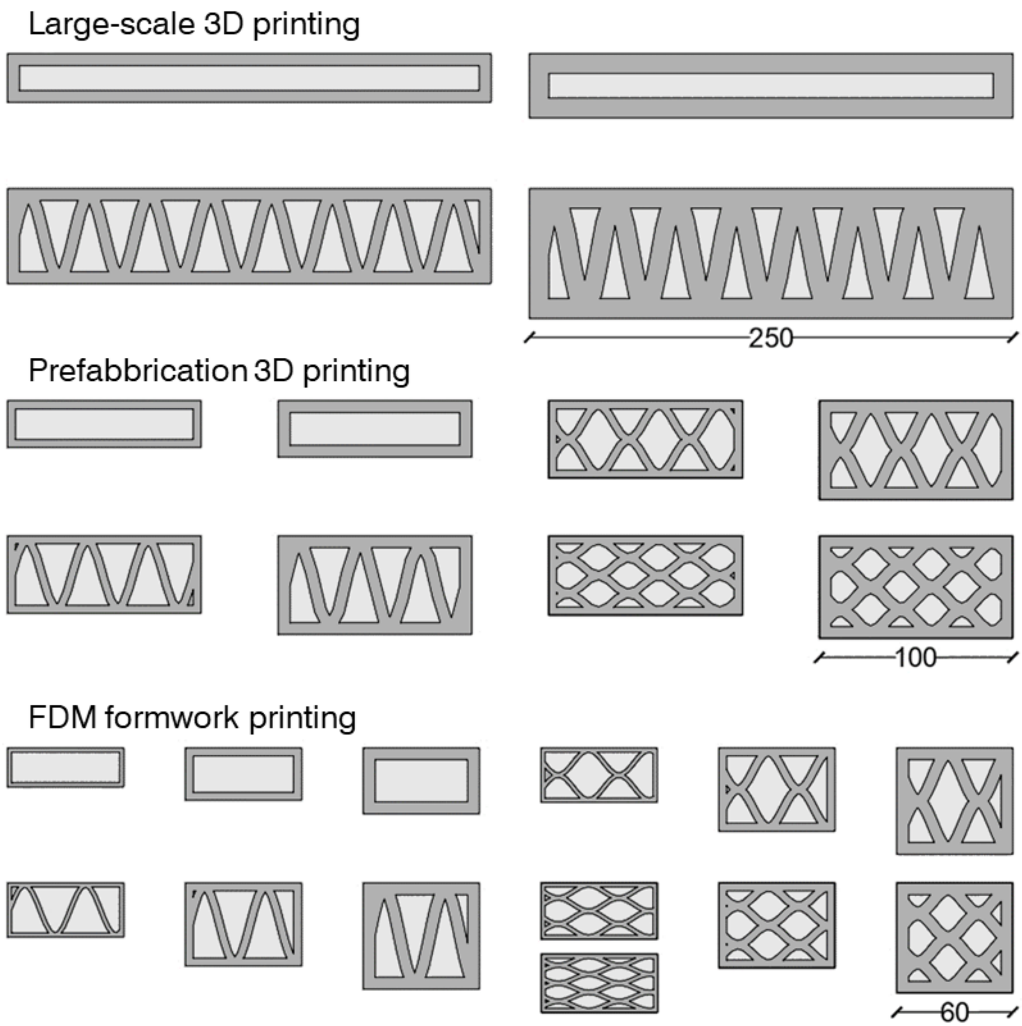


Fig. 30 - 3D printed envelope configurations.

Tab. 11 summarizes the various configurations explored in relation to the printing technology and their respective parameters. Each configuration was then analyzed using LCA to compare the environmental impact of different printing technologies under identical thermal performance conditions.

Tab. 11 Configurations parameters and iterative thermal analysis results.

3D printing technology	Configuration Name	Wall width Y [cm]	Wall thickness T [cm]	Sinusoids number NS	Wall length X [cm]	Thermal transmittance TT [W/m^2K]
Large-Scale 3D printing	Monolithic 6-0	25	6	0	250	0.2906
	Monolithic 6-1	49	6	1	250	0.2919
	Monolithic 10-0	33	10	0	250	0.2832
	Monolithic 10-1	67	10	1	250	0.2915
3D printing for precast	Prefabrication 4-0	24	4	0	100	0.2878
	Prefabrication 4-1	40	4	1	100	0.2896
	Prefabrication 4-2	40	4	2	100	0.2866
	Prefabrication 4-4	41	4	4	100	0.2852
	Prefabrication 6-0	29	6	0	100	0.2887
	Prefabrication 6-1	51	6	1	100	0.2890
	Prefabrication 6-2	51	6	2	100	0.2900
	Prefabrication 6-4	53	6	4	100	0.2853
FDM-based formwork	FDM formwork 2-0	20	2	0	60	0.2941
	FDM formwork 2-1	28	2	1	60	0.2935
	FDM formwork 2-2	28	2	2	60	0.2890
	FDM formwork 2-4	29	2	4	60	0.2831
	FDM formwork 2-6	30	2	6	60	0.2866
	FDM formwork 4-0	27	4	0	60	0.2935
	FDM formwork 4-1	43	4	1	60	0.2896
	FDM formwork 4-2	43	4	2	60	0.2870
	FDM formwork 4-4	44	4	4	60	0.2849
	FDM formwork 6-0	34	6	0	60	0.2900
	FDM formwork 6-1	55	6	1	60	0.2918
	FDM formwork 6-2	55	6	2	60	0.2928
	FDM formwork 6-4	57	6	4	60	0.2868

A multilinear regression analysis was conducted to estimate the relationship between the independent variables and the wall width considering the same thermal transmittance. The resulting equation for the model is presented below.

$$Y = -507.266 + 5.886\,T - 0.054\,X + 5.439\,NS + 1781.206\,TT$$

- Y= wall width

- T= wall thickness
- X= wall length
- NS= Sinusoids number
- TT= Thermal transmittance

7.4.2. Life cycle assessment results

This section reviews the Life Cycle Impact Assessment results for GWP and CED for the three presented technological scenarios. The analysis identifies both the advantages and disadvantages of different construction techniques, offering insights for improving environmental sustainability. Fig. 31 shows the GWP results of the various configurations using the three production scenarios.

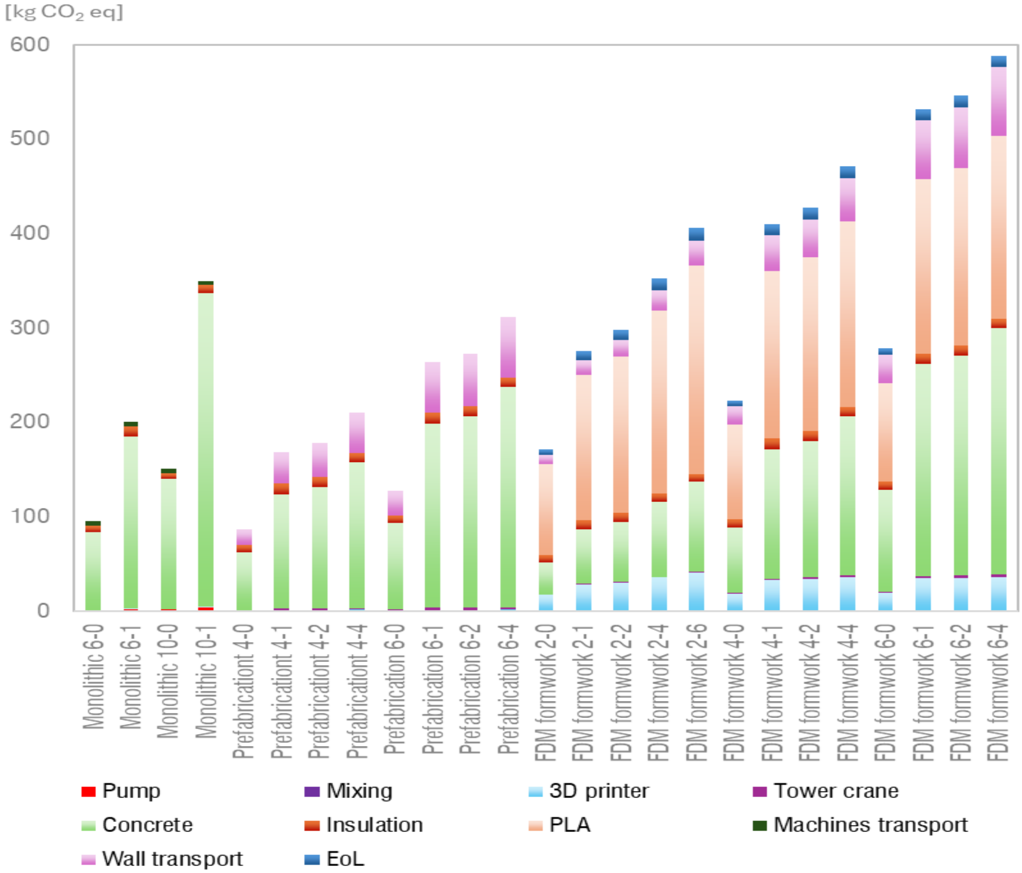


Fig. 31 - GWP results of the different configurations using the three scenarios of production.

The impacts of building envelopes depend on the technology and configuration, ranging from 88.26 kg CO2 eq and 1257.72 MJ to 588.89 kg CO_2 eq and 9170.67 MJ. At the same time, both impact categories exhibit similar trends and percentage contributions.

- *Scenario 1: Impact of Large Gantry System for Monolithic Construction*
  Monolithic 3D printing using a gantry system primarily impacts because of the concrete production phase, which contributes 95% of the total, due to the large volume of material and the unitary GWP of concrete (660 kg CO_2 eq per m^3). This attitude is in line with previous studies on traditional and innovative 3D printed concrete buildings [257,258]. The impacts increase with greater geometric complexity (e.g., larger nozzle diameter), leading to higher material usage.
  Concrete constituent analysis shows that Portland cement has the greatest environmental impact, while other materials of the cementitious admixture have minimal effects. Even though PP fibers represent less than 1% of the material, they contribute 4% of GWP. Sustainable alternatives, like geopolymer concrete or recycled PP fibers, could reduce the environmental footprint [259,260].
  The COBOD 2 3D printer's energy consumption is negligible, making up about 1% of the total impacts, with high productivity and low energy use (1 kW). This could promote wider industrial adoption of 3D printing technology without significant energy increases.
  Insulation materials, such as cellulose fibers, have lower GWP impacts (2-7%) compared to concrete, due to their low density and unitary GWP. However, they account for up to 40% of CED results due to the energy-intensive production process, though CO_2 emissions remain low thanks to renewable energy sources.
  Transport of machines contributes 1-5% of the total impact, with 4.6 kg CO_2 eq and 75 MJ, despite the considerable weight (8000 kg) and transport distance (500 km). These impacts are distributed across the

entire construction process and are relatively low, particularly with on-site construction reducing the need for transporting precast materials. The growing adoption of 3D printing in situ is expected to reduce transport distances.

- *Scenario 2: Impact of 3D Printing Prefabrication with Gantry System*
  In Scenario 2, as in Scenario 1, most impacts come from concrete production and transportation, contributing 70-75% of the total. Wall depth, wall thickness and geometric complexity influence concrete usage, increasing impacts. Unlike Scenario 1, transportation is a significant factor in prefabrication, as prefabricated components need to be transported to the site, contributing 5-20% of GWP. On-site production could mitigate this. The energy consumption of the SMART 2500 printer is low, with a smaller nozzle but similar productivity to Scenario 1.
  When comparing configurations with same wall thickness (e.g., Monolithic 6-1 and Prefabrication 6-1), Scenario 2 has higher impacts due to transportation. However, prefabrication allows for thinner walls with more intricate shapes, making some configurations (e.g., Prefabrication 4-0) more sustainable than any in Scenario 1 due to reduced material usage.
- *Scenario 3: The Impact of FDM formwork Prefabrication Technique*
  The same considerations related to transport and material use can be applied to the third scenario since FDM-based formwork production is a prefabrication technique. In Scenario 3, the main contributor to environmental impacts is PLA pellet production, accounting for 33-60% of total GWP and CED. While PLA is considered a sustainable, biodegradable thermoplastic material [261], its production and use in 3D printed formworks require substantial material (31.4-63.1 kg). Complex infill patterns increase both PLA and concrete use, reducing overall sustainability.

FDM-based formwork technology can create extremely thin concrete walls, minimizing raw material use. Configurations like FDM formwork 2-0 and 2-1 have the lowest concrete usage. However, FDM printers used in this technique are less productive, with much lower output (3.5 kg/h) than concrete printers, consuming more energy per kilogram of material. This lower productivity is primarily due to the smaller nozzle dimensions (0.5 cm). Future advancements in FDM efficiency could improve the sustainability of this approach.

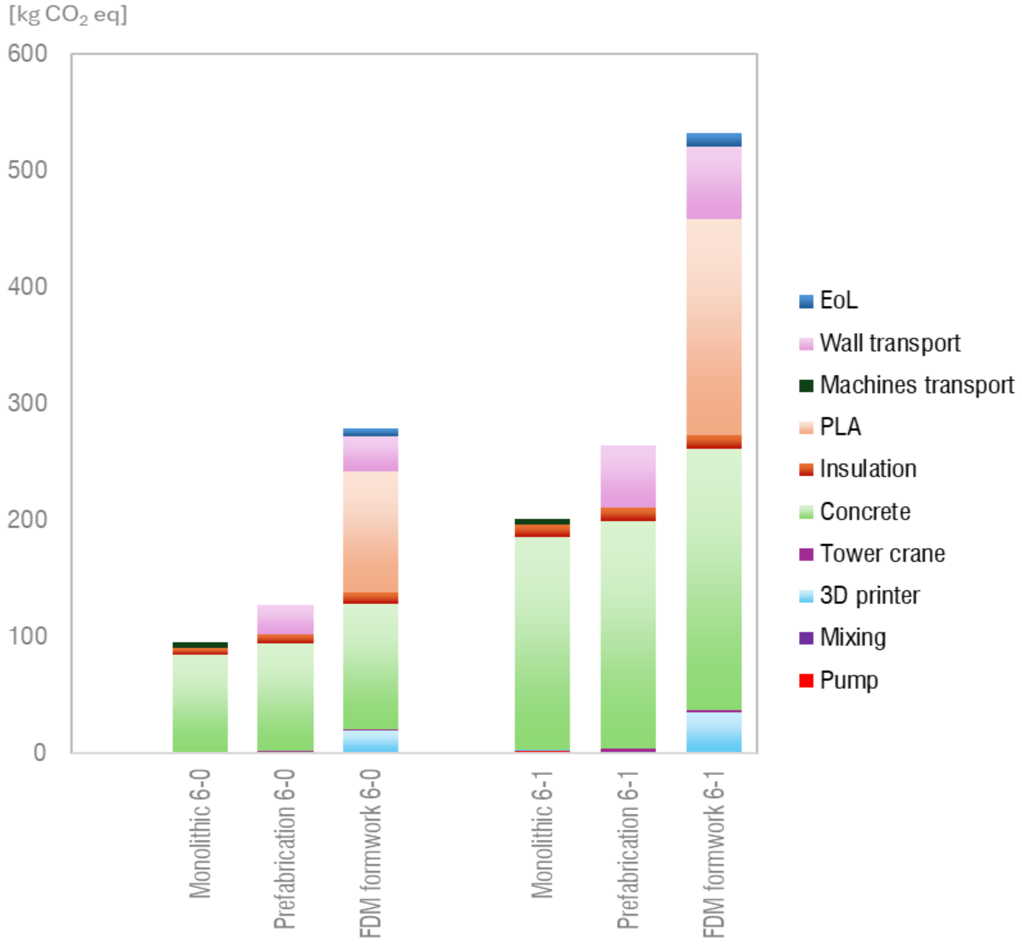


Fig. 32 - Comparison of the GWP of the same geometrical configuration realized with three different printing productions.

Fig. 32 highlights the Comparison of the GWP of the same geometrical configuration realized with three different printing productions. Both configurations (6-0, 6 cm of wall thickness without internal pattern and 6-1, cm of wall thickness and 1 internal sinusoid) have the highest impacts if produced with FDM formwork technology. Monolithic production and prefabrication have lower impacts, and their gap is mainly caused by transport. At the same time, it is important to emphasize that FDM-based formwork technology enables a degree of resolution that cannot be achieved with other technologies making it a viable alternative in case of specific design requirements.

The analysis highlights the importance of reducing concrete use for environmental sustainability. Between concrete weight and GWP across all scenarios there is nearly a linear relationship, with heavier configurations causing higher impacts. Scenario 1 (monolithic construction) is the most sustainable due to on-site printing, which avoids transportation. However, Scenario 2 could match this by implementing prefabrication on-site. Scenario 3 currently has the highest impacts due to transport and FDM printer inefficiencies, but future improvements in material use and renewable energy could make it more sustainable. Reducing wall thickness and nozzle diameter, as seen in Scenarios 2 and 3, leads to lighter buildings and sustainability improvements over Scenario 1's heavier designs.

7.5. Conclusions

The introduction of 3D printing technology into the construction sector marks not just an evolution but a transformative shift in construction methods. It unlocks new possibilities, redefines design, boosts performance, and promotes sustainability in building and architecture. This chapter examines the thermal properties and environmental impacts of three emerging additive manufacturing technologies for constructing building envelopes. Specifically, it investigates 3D printing using large gantry cranes for monolithic construction (scenario 1), small gantry cranes for prefabrication (scenario 2), and FDM technologies for FDM-based formwork techniques (scenario 3), respectively.

This study explores how these three approaches can be applied to create different configurations of building envelopes with specific performance targets. The iterative design and thermal analysis methodology was implemented with a single automated algorithm that closely links configuration and thermal analysis. The phase of performance study of the adopted method, in addition to thermal analysis, assesses the environmental impact of the envelope components on development. An LCA analysis has been conducted to explore the sustainable potential of cited 3D printing technologies. This comprehensive study provides valuable insights into the sustainability and performance of different production technologies making manufacturing technology a parameter to be evaluated in terms of sustainability in the building component development process. In all scenarios, concrete production is one of the most environmentally impactful phases, contributing up to 95% of the total environmental impacts.

Generally, increasing the number of infill sinusoids and wall thickness leads to higher material use and environmental impacts. Thus, thin walls made through prefabrication and FDM-based formwork techniques could improve sustainability by reducing raw concrete impacts while maintaining thermal performance. 3D printers used for monolithic construction and prefabrication have low energy consumption and high productivity. The energy and resource consumption to operate these 3D printers is minimal (about 1% of the total footprint). These printers also appear to be the most sustainable options when comparing similar geometric configurations. FDM-based formwork significantly raises environmental impacts due to raw PLA production and machine energy use. Scenario 3 impacts could be reduced by using recycled materials and sustainable energy sources, potentially bringing its impacts closer to those of the other two scenarios. These findings offer valuable insights for both researchers and construction companies looking to improve the sustainability of their 3D concrete printing processes. Future research will focus on different infill configurations and potential improvements. Life Cycle Costing analyses will also be performed to provide a more complete view of the economic impacts of the scenarios. Together with the LCA, these results will offer a comprehensive decision-making tool for adopting 3D printing technologies in construction.

8. PROTOTYPING: development and printing of a cement-based envelope system

8.1. Introduction

Research and development work on the integrated methodology to support the design of 3D printed building components led to the prototyping of a cementitious envelope element. This final chapter presents experimental work on developing and prototyping an envelope system of prefabricated cementitious elements with 3D printing. Specifically, the work was conducted in response to the last two research questions. In fact, a preliminary phase focused on modifying a cementitious mixture to improve its performance according to the printing requirements, responding to **RQ8**. In addition, to respond to **RQ9** regarding the optimization of geometry concerning printing requirements, 3D printing tests were conducted to adapt the initial geometry. Finally, a full-scale element was prototyped.

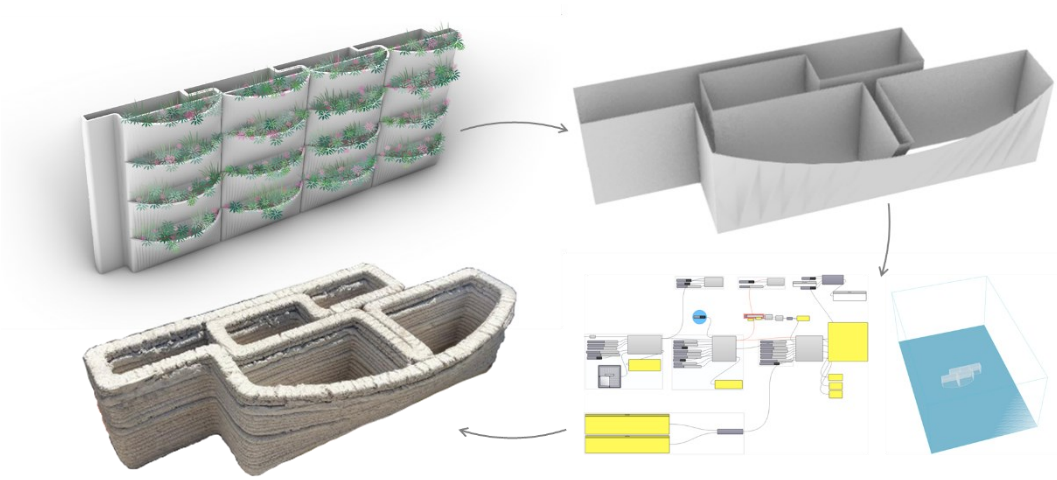


Fig. 33 Process representation of the development and printing of a cement-based envelope system

8.2. Envelope system design

The design of the envelope system was developed from an earlier work by the same author [222]. The system consists of a series of modular interlocking elements that can be prefabricated by 3D printing and assembled on-site. Each block is designed to perform different functions such as thermal insulation, structural reinforcement, and building services integration. The empty spaces in fact can serve as formwork for reinforced concrete pillars, contain precast structural elements, contain systems integrated into the masonry, or be filled with insulating material. The assembly of the elements makes it possible to prevent the discontinuity of thermal insulation thanks to half-lap joints. The cross-sectional geometry increases the thermal path and thus avoids thermal bridges. In addition, a curved pocket design has been devised, easily achieved with 3D printing, which can be filled with soil to create a green wall. The use of green walls for buildings has the dual functionality of increasing green surfaces in the urban environment and increasing thermal inertia of the envelopes due to the mass of the soil.

The design concept behind the modular elements system is to adapt geometries and dimensions to specific contexts and requirements. The developed methodology applied to the described system allows for the parametrization of the elements and the variation of the single design to achieve specific project targets. Different elements can also be combined to achieve different purposes.

8.3. Cement mixture development

The selection of the cement mixture to be adopted was based on commercial mortars intended for applications other than 3D printing. In particular, three cement mixtures by Kerakoll were evaluated.

- *Benesserebio®* is made of Natural Hydraulic Lime (NHL) improved with mineral geo-binder, natural amorphous pozzolan and natural active principles. The product has thermo-evaporating power, is warmer and thermally insulates the wall. It is particularly suited to create plasters/renders.
- *GeoCalce® G anti-seismic* is a structural geo-mortar made of NHL and geo-binder. It is suitable for consolidation and repair of masonry works.
- *GeoCalce® Tough* is a geo-mortar made of NHL and geo-binder with anti-crack fibre. Specifically designed for guaranteed anti-crack plastering/rendering, for the structural strengthening of buildings, and for

infill masonry as an anti-collapse and break-away protective system for brick and cement floor slabs.

The three products were considered because an evaluation of the composition indicated that they might already have properties such as strength and fluidity that are suitable for 3D printing.

8.3.1. Sample printing test

First, mixtures were created respecting the water-cement ratios suggested by the data sheets, and manual extrusion tests were subsequently performed. These initial tests allowed the water-cement ratios to be experimentally varied to improve extrudability and buildability. The water-cement ratios deemed best were then optimized by employing super-plasticizing additives. In particular, Sika's ViscoCrete-20HE was added as a percentage to the cement mixture. In addition to manual tests, printing tests were then conducted employing the Delta WASP 2040 printer and the Be more 3D printer, which will be used in full-scale prototyping. Specifically, the different cement mixtures were evaluated in stages concerning optimizing the printing properties for the large-scale Be more 3D printer. Tab. 12 contains the characteristics of the different printing tests conducted. Summarizing, the tests of the three kinds of cement admixture have been performed with manual extrusion, a small 3D printer (Delta WASP 2040) and a large-scale 3D printer (Be more 3D); with different water-binder ratio; and with different additives-binder ratio.

Tab. 12 Extrusion and printing tests of different cementitious binder mixtures with different water-binder ratios and different additives-binder ratios.

Binder	**Test**	**Water-binder %**	**Superplast %**
Benesserebio®	Manual extrusion	33.40%	0.00%
Benesserebio®	Manual extrusion	20.00%	0.00%
Benesserebio®	Manual extrusion	22.00%	0.00%
Benesserebio®	Manual extrusion	24.00%	0.00%
Benesserebio®	Manual extrusion	25.00%	0.00%
Benesserebio®	Manual extrusion	27.00%	0.00%
Benesserebio®	Manual extrusion	28.00%	0.00%
GeoCalce® G anti-seismic	Manual extrusion	20.00%	0.00%

GeoCalce® G anti-seismic	Manual extrusion	30.00%	0.00%
GeoCalce® G anti-seismic	Manual extrusion	25.00%	0.00%
GeoCalce® G anti-seismic	Manual extrusion	23.00%	0.00%
GeoCalce® G anti-seismic	Manual extrusion	20.00%	1.00%
GeoCalce® G anti-seismic	Manual extrusion	15.00%	1.00%
GeoCalce® G anti-seismic	Manual extrusion	17.00%	0.50%
GeoCalce® G anti-seismic	WASP 3D printer	21.50%	0.00%
GeoCalce® G anti-seismic	WASP 3D printer	22.00%	0.00%
GeoCalce® G anti-seismic	WASP 3D printer	23.50%	0.00%
GeoCalce® G anti-seismic	WASP 3D printer	25.00%	0.00%
GeoCalce® G anti-seismic	Be more 3D printer	21.00%	0.00%
GeoCalce® G anti-seismic	Be more 3D printer	20.00%	0.00%
GeoCalce® G anti-seismic	Be more 3D printer	20.50%	0.00%
GeoCalce® Tough	Manual extrusion	15.00%	1.00%
GeoCalce® Tough	Manual extrusion	12.00%	1.00%
GeoCalce® Tough	Manual extrusion	17.00%	0.50%
GeoCalce® Tough	WASP 3D printer	20.50%	0.00%
GeoCalce® Tough	WASP 3D printer	20.00%	0.00%
GeoCalce® Tough	Be more 3D printer	17.00%	0.24%
GeoCalce® Tough	Be more 3D printer	12.00%	1.00%

Test results led to the first exclusion of Benesserebio® as although performing well from a printing point of view, the dry products are too fragile for the design purpose. The other two cement mixtures yielded good results for large-scale printing with a water-cement ratio of 20.5% without additives and a water-cement ratio of 12% adding 1% super-plasticizer. Therefore, the use of the super-plasticizing admixtures allows for the reduction of the water-binder ratio and thus the overall weight of the fresh mortar. During the printing phase, this feature is critical to increase buildability by reducing the risk of collapse and crushing of the lower layers.

8.3.2. Thermal transmission test

Tests were conducted on the various samples to attest to their thermal conductivity. ISOMET 2114, a hand-held measuring instrument for direct measurement of heat transfer properties, has been employed. The device automatically makes two measurements of which the average is calculated.

Tab. 13 resumes the samples analyzed with the respective production type (casted or printed), curing time, and conductivity results. The dimensions of each sample are 10 cm x10 cm and the thickness is 4 cm. Measurements were conducted on samples with the same cement mixture with different setting times (after 24 hours and after one week of baking, respectively). Samples were made both cast in molds and 3D printed with the machine then used for final prototyping. Initial analyses showed no significant difference in conductivity between the two types of realization either at 24 hours or at one week of setting. This comparison, shown in graphs (Fig. 34), demonstrates that the production method with 3D printing does not affect the bonding reactions between layers of fresh cement admixture, making casted and printed elements completely comparable from the point of view of thermal performance. Moreover, the use of additives in the mixture leads to increased conductivity yet not excessively.

Tab. 13 Thermal conductivity of different cementitious samples casted or printed comparing their curing time.

Name	**Type**	**Time curing**	**Conductivity average [W/m K]**	**Conductivity measurement 1 [W/m K]**	**Conductivity measurement 2 [W/m K]**
GeoCalce® G anti-seismic	3D printed	1 month	1.0552	1.0552	/
GeoCalce® Tough	3D printed	24 h	1.451	1.4533	1.4486
GeoCalce® Tough + additives	Casted	24 h	1.7476	1.7425	1.7528
GeoCalce® Tough	Casted	24 h	1.4128	1.4181	1.4075
GeoCalce® Tough	3D printed	1 week in oven	0.7933	0.7931	0.7935
GeoCalce® Tough + additives	Casted	1 week in oven	1.0708	1.0701	1.0714
GeoCalce® Tough	Casted	1 week in oven	0.7371	0.7344	0.7397

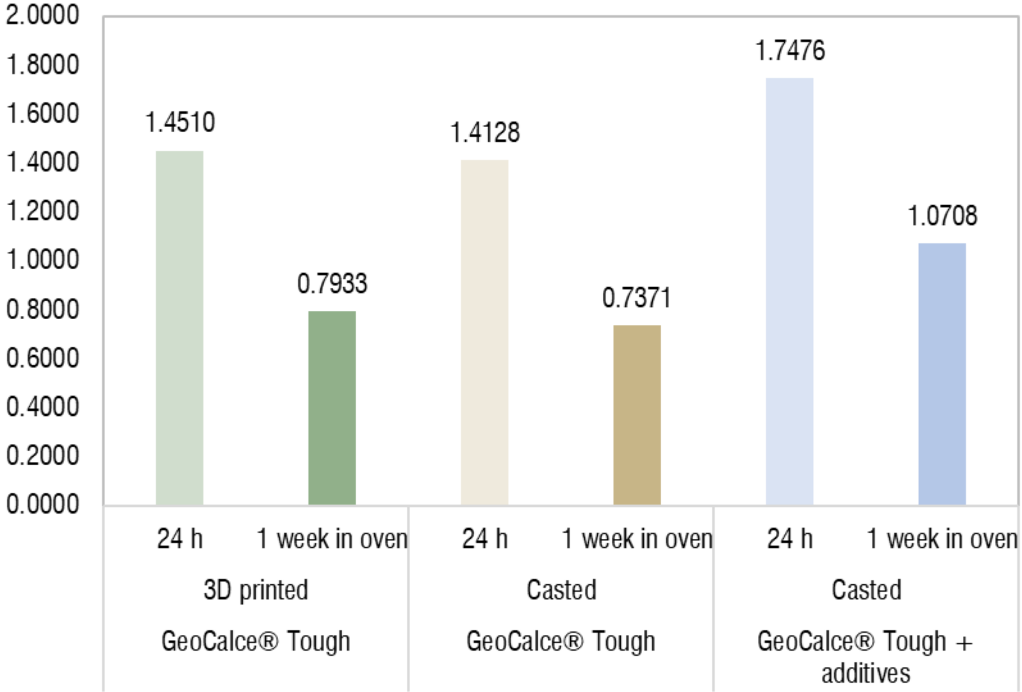


Fig. 34 Graphic representation of thermal conductivity [W/mK] of different cementitious samples casted or printed comparing their curing time.

8.3.3. Compression and flexural strength tests

During the printing tests with the Be More 3D printer, prismatic samples were cut for subsequent flexural and compression testing. The two samples were made of GeoCalce® Tough with 12.00% water and 1% additives. Flexural and compressive strengths were measured after 30 days of curing.

The flexural tests were carried out at a loading rate. Each half part of the broken samples from the flexural strength test was used for the compressive strength test at a loading rate. Each measurement was replicated, and the average value was taken as the value of strength. The results are a flexural strength of 0.808 MPa and a compressive strength of 11.231 MPa.

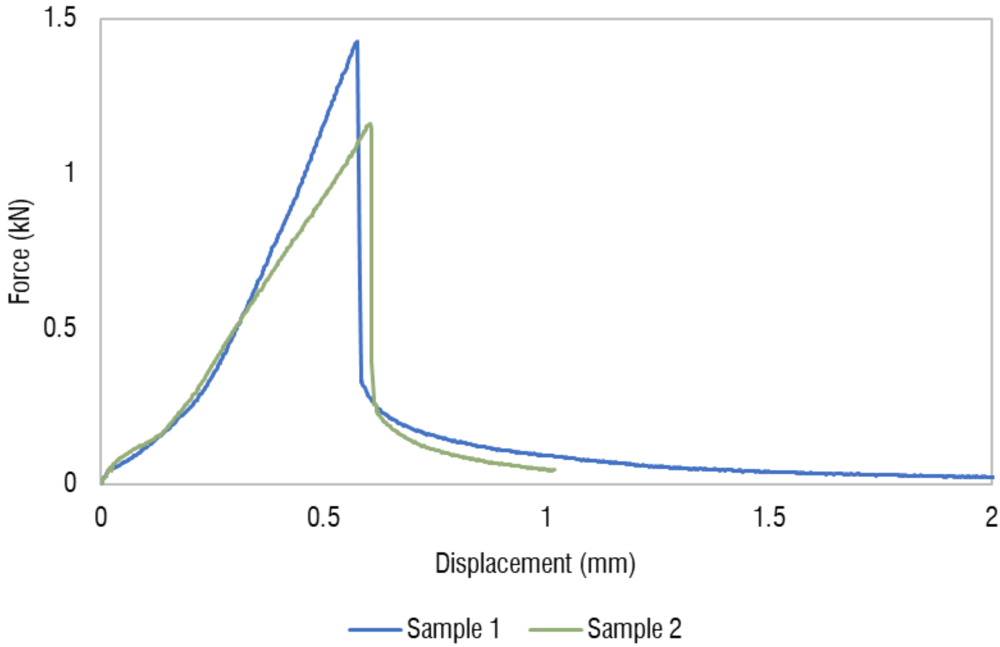


Fig. 35 Flexural strength of 3D printed samples with an average value of 1.293 kN.

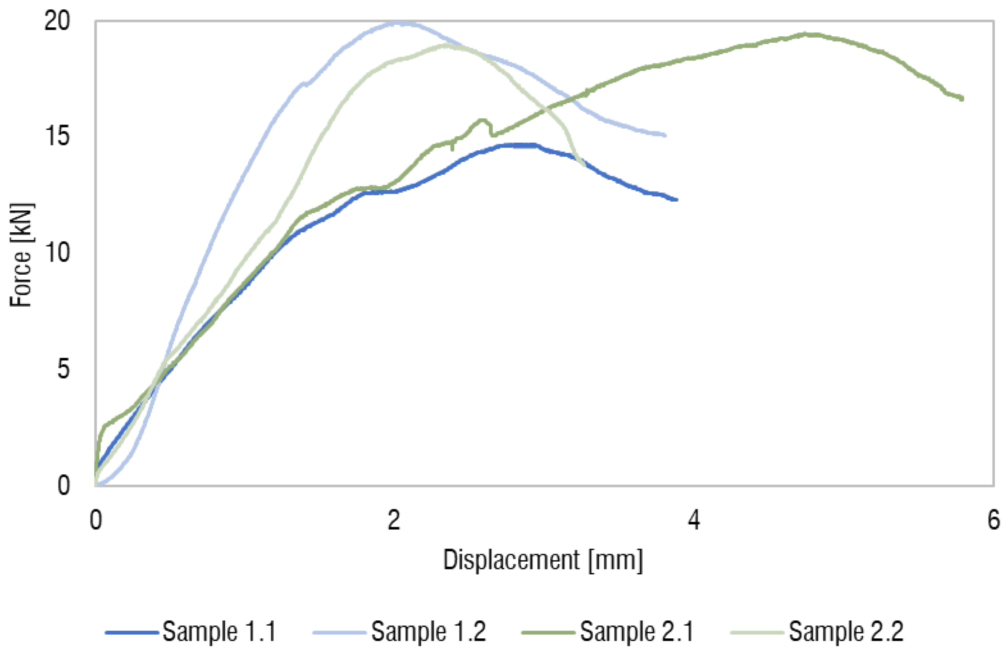


Fig. 36 Compressive strength of 3D printed samples with an average value of 17.969 kN.

8.4. Prototype development

8.4.1. Parametric model and G-Code development

The parametric model was developed with Grasshopper (Fig. 37). Parameterization allows not only to change the size and proportions of the designed element but also, in this specific model, to change the pocket width and internal geometry.

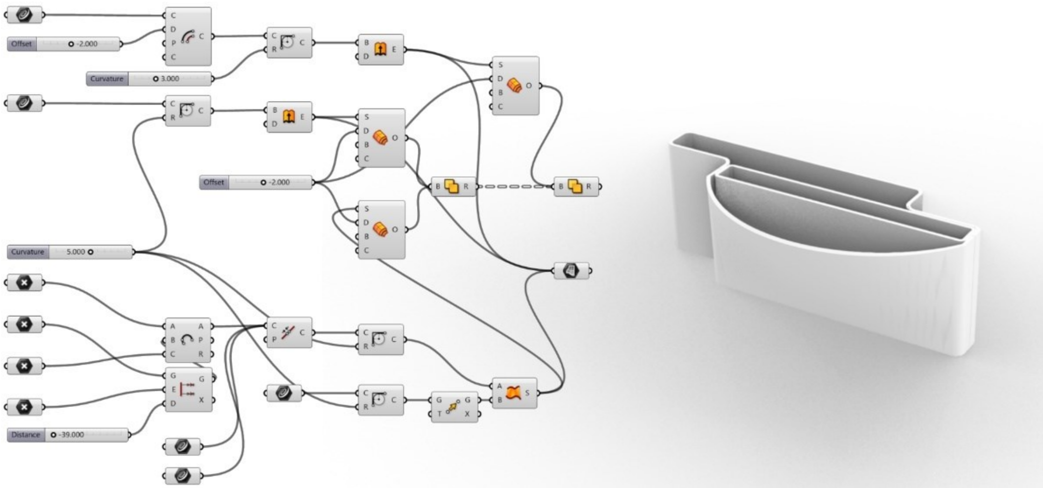


Fig. 37 Parametric 3D model.

The model defined in surfaces was then connected to an algorithm always present in Grasshopper that leads to the processing of the G-code subsequently read from the 3D printer (Fig. 38). The first step in the implementation of the printing algorithm is the configuration of the machine. The x,y and z Cartesian measurements of the printer are entered to define the printing area. The geometry can then be located. The second phase concerns model slicing. For this step, input data are entered. This data can be modified later according to the results of print tests. The inputs are slicing distance, noozle diameter, number of base layers, base infill-wall offset, base infill-line distance, number of walls and spiralization mode. The third part of the algorithm regards the printing parameters. The parameters are print speed, jog speed, extruding amount, retraction amount, extrusion wait time, z base offset and start-end G-code. In particular, the start-end G-code constitutes the initial and final parts of the code that are strictly dependent on the printer in use. Finally, the algorithm allows the complete G-code to be exported.

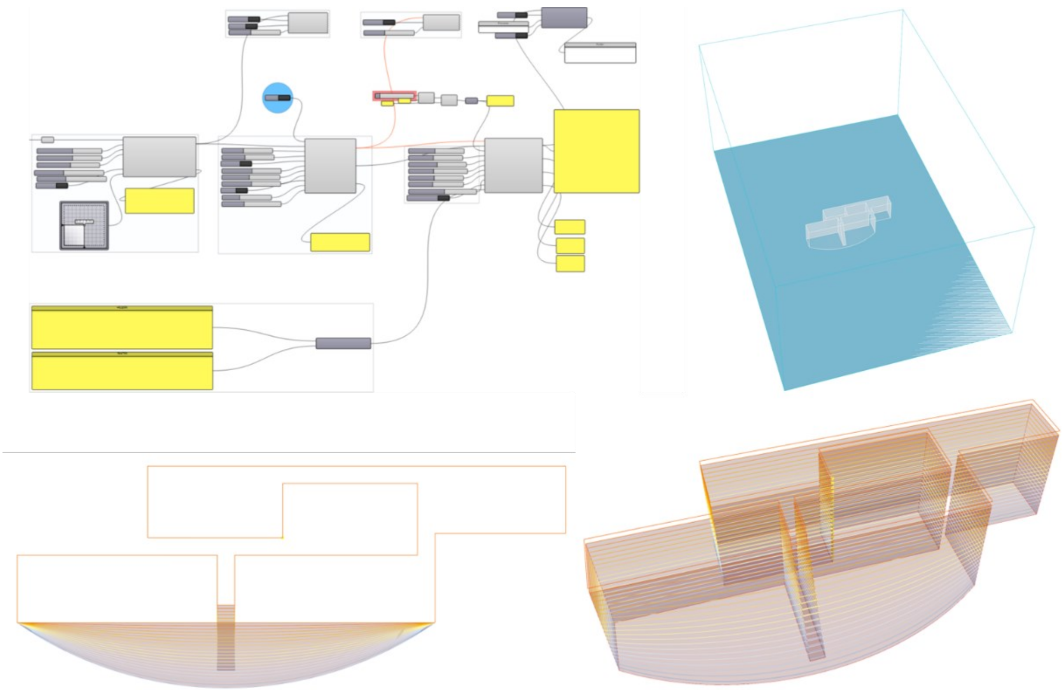


Fig. 38 Algorithm to create the G-code of the prototyped configuration.

8.4.2. Print test and geometry adaptation

The printing process has been performed using as reference the "SMART 2500" model, a granty-crane 3D printer from the company Be More 3D [113]. The installable nozzles allow a wall thickness of 20 mm to 60 mm. The speed range is from 20 mm/s up to 150 mm/s. The printing area is 3 m wide and 6 m long (up to a maximum of 3 m in height). It requires a team of 2-3 people to operate. Also, the 3D printing phase requires support from additional machinery such as concrete mixers.

Printing tests were conducted by varying and optimizing the cement mixture, printing parameters and element geometry. As a first printing strategy, the models were printed upside down in order to avoid outward projecting parts. The major obstacle to overcome was to prevent layers' collapse due to the slenderness of the walls and the breakage of the sloping surface of the element (Fig.39). To this end, geometries that would forge capable of self-supporting were experimented with. Fig. 40 shows different configurations tested. Tests have shown that creating walls with a lower length-to-thickness ratio and adjacent to perpendicular walls allows greater heights to be achieved before collapse.

Fig. 39 Example of layers' collapse, probably due to the slenderness of the walls and the breakage of the sloping surface.

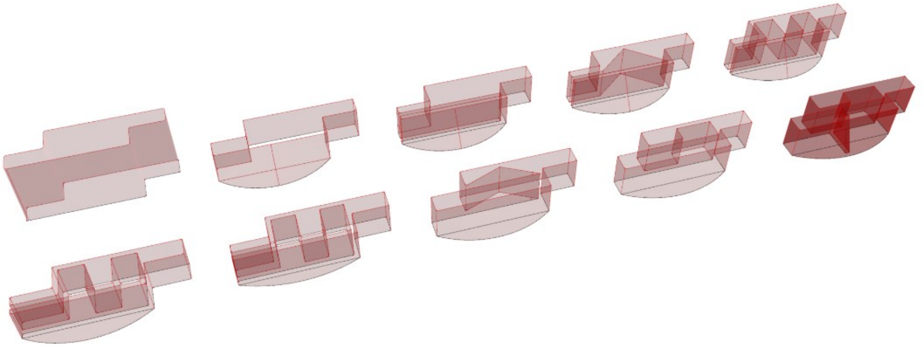


Fig. 40 Examples of different configurations tested.

8.5. Results

After several tests, the final full-scale printed configuration has been reached. The cementitious mixture is composed of GeoCalce® Tough with a water-binder ratio of 12.00% and 1.00% of additives. Compared to the initial model, the internal geometry has been subdivided into smaller cells. This made it possible to avoid the formation of long, slender walls by creating internal baffles for self-supporting. In particular, the pocket is divided by a triangular wall, which in the printing phase made it possible to support the load of the fresh mortar layers of the sloping wall. In addition, geometry is designed to create a continuous path during extrusion to improve print quality. One month after printing, as predicted by the material strength tests, the element's strengths were sufficiently developed to allow it to be overturned. This operation has in no way damaged its integrity (Fig. 41).

Fig. 42 shows the dimensions of the prototyped element. Specifically, the prototype is 130 cm in total length, 40 cm in total width. Each layer is 1,5 cm high and 4 cm thick. The other dimensions are x=100 m, y=20 cm, w=30 cm and z= 30 cm.

Fig. 41 Pictures of the final 3D printed component (after the printing phase).

Fig. 42 Perspectives of the reverse printed component in its utilization position (after one month of setting).

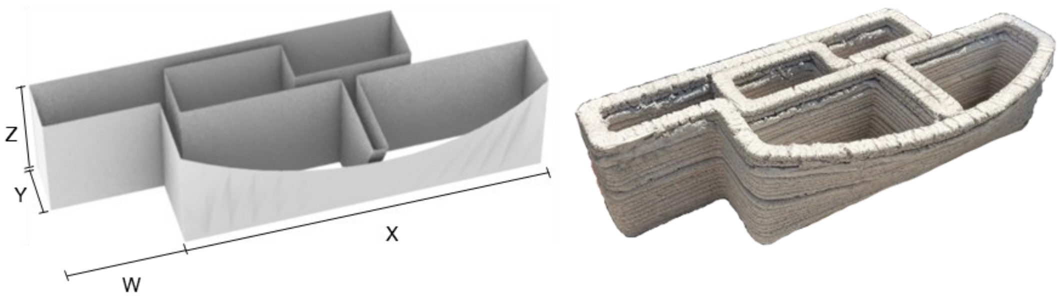


Fig. 43 3D model of the final configuration (x=100 m, y=20 cm, w=30 cm, z= 30 cm) and prototyped component.

9. CONCLUSIONS

The main aim of the present dissertation is to explore the possibilities that 3D printing offers to the construction industry. The work has been developed by investigating and overviewing additive manufacturing technologies focusing on the different types of materials that can be employed and related applications. Among the various additive printing technologies, material extrusion is the most commonly investigated to be engaged in the construction industry. Alongside, research and prototype in such field are predominantly focused on cement and concrete due to their widespread use and lower costs. While 3D concrete printing is becoming a widely adopted building technology, the printing of construction components using clay, steel, or glass remains largely experimental (**Chapter 2**).

The research proceeded with a comparison between an in-depth bibliometric review and a market survey in the field of 3D construction printing. This comparison provides a comprehensive overview of how the academic and technical worlds are differently approaching 3D construction printing, examining both gaps and potentials. Firstly, the research focuses on a parallel comparison between academic research and the construction market through two dedicated sections. One section details the development of 3D printing technology in academic research, emphasizing temporal and spatial information. Another section surveys all 3D printed buildings developed to date and examines the current companies involved in 3D printed building production. Secondly, the results have been discussed by outlining a roadmap of stages and future directions of technology and by highlighting current limitations and unresolved scientific questions. In total, over 1,800 scientific works in the field of 3D construction printing were analyzed, with the data used to create suitable charts, maps, and trend diagrams. Additionally, in the construction market, more than 80 3D printed structures were identified, and 71 companies were examined. The findings indicate that the main limitations of 3D printed buildings include their reduced size, structural performance, the printing of horizontal surfaces such as slabs, and the difficulty of incorporating reinforcements directly during the printing process. Out of this preliminary overview, despite the widespread application of 3D printed buildings by companies, research topics with open questions have been evinced. The review reveals a significant lack of scientific knowledge regarding the actual performance, durability, sustainability, life cycle environmental impact, and circular design of printed structures (**Chapter 3**).

Some considerations about how 3D printed building components can meet multi-objective performance have been elaborated with the consequent formulation of the research question. For 3D printing to become an established technology in construction, the printed products must be competitive in terms of performance within the existing market. As a response to the research question, the present work proposes a methodological approach based on parametric design supported by an iterative performance analysis to obtain building envelope components. This allows for the creation of adaptable building elements suitable for different boundary conditions and prefabricated using 3D printing technology. The proposed methodology follows a four-phase iterative process: I. design development and parametric modelling; II. definition of performance criteria and boundary conditions; III. performance simulation and parameter identification; IV. production with 3D printing. In particular, the first three phases are repeated until the model's parameters are refined to achieve optimal performance under the specified conditions. The application of this process leads to enhancing the performance by combining the iterative process (based on parametric modelling and performance analysis) and the advantages of a 3D printed prefabricated component. Its effectiveness is attributed to the possibility of modifying the parameters of the component (with high geometrical freedom) in order to improve its performance while regarding also printability. The methodological approach can be adapted to evaluate different aspects of building engineering design by relating multiple simulation systems (energy, acoustic, structural, environmental impact, life cycle, etc.) and related targets to be satisfied. The methodology would provide support to the design choices for the component considering the combinations of different parameters and the limitations imposed by production technology (**Chapter 4**).

The methodology for supporting the project of 3D printable envelopes was then employed for different applications and relative case studies refining the process.

Applications tackled aim to make the process of optimizing parameters, depending on boundary conditions, increasingly automated. Starting from a manual iterative method, that consisted of changing parameters and then repeating the simulations, a workflow was developed that allows for automatic simulations as parameters change until the target is reached. A common aspect of the case studies developed concerns the use of 3D printing as a technology for the prefabrication of building components rather than on-site production of large-scale buildings providing examples of employment. As the thermal performance aspect of printed building elements has not yet been sufficiently investigated, it has become one of the recurring research questions in the applications of the developed methodology. Among the different performance characteristics (acoustic, structural, environmental impact, life cycle, etc.) that a building component must expect, the case studies under investigation focus on the fulfillment of thermal performance. This characteristic, as introduced, is of fundamental importance for the actual use of the designed building products. In addition, the applications are intended to demonstrate the correlation that can occur between geometry and thermal path affecting the total transmittance of an envelope, and thus the concrete advantage that can be derived from the use of 3D printing, which allows a high degree of geometrical freedom.

In particular, *Application 1* represents the first application of the proposed methodology. The related case study concerns the design of an envelope component supported by parametric modeling and prefabricated with 3D printing. The parametric 3D model was developed using Grasshopper defining variable geometrical parameters such as the length of the half-lap joints, corner curvature, boundary thickness, spigot and socket joint thickness, and the adjustable filling pattern of the air cavity and insulation panel thickness. The thermal transmittance limits of external walls for different climatic zones (according to a specific regulation) have been used as a reference for setting the required performance targets. The thermal analysis is conducted using FEM simulations in ANSYS R22 software to assess heat transfer and heat flux performance. The geometrical parameters have been adjusted and analyzed using an iterative process in order to identify the best components configuration to operate in a specific external environmental condition. The iterative design process results in five different configurations of the 3D printed envelope, each tailored to meet the regulatory requirements of the different Italian climate zones. The adopted approach allows for the identification of multiple design solutions, with the ability to quickly modify the 3D model based on the desired performance. The iterative approach, coupled with the flexibility and customizability of 3D printing, provides significant advantages during the design phase. The component parameters can be adjusted to improve performance without the need for complete re-modeling while maintaining printability. Additionally, parametric design enables the evaluation of the impact of individual parameters on thermal performance by simply altering one variable at a time. Moreover, thanks to the iterative methodology it is possible to generate multiple configurations, enabling the simultaneous analysis of a variety of design solutions. This approach prevents unnecessary performance maximization where it is not needed, thus conserving materials (**Chapter 5**).

Application 2 introduces a preliminary step to the methodological approach for designing efficient 3D printed building envelopes incorporating reused materials in the printing mixture and insulation filler. The process begins with defining the reuse design by selecting materials for recovery, followed by parametric modeling and simulation to optimize the block's shape, and finally, identifying the best settings for 3D printing production in a specific boundary condition. This approach is applied to two different case studies using a mortar with recycled glass or rubber for the printing mixture and glass fiber or cellulose for the insulation layer. The first case study involves the envelope component introduced in the previous chapter analyzing possible thermal performances using recycled materials. The second case study focuses on applying the methodology involving recycled materials to the design of an envelope system made up of modular 3D printable components. The structure follows a hexagonal pattern, which is easily manufacturable using 3D printing technology. The geometry of these elements enables both interlocking and the filling of the hexagonal cells with insulating material, enhancing thermal performance. Through this approach, both elements of the two case studies were thermally optimized by adjusting geometric and material parameters based on specified boundary conditions. Two different 3D printing admixtures were evaluated, both using cement-based materials (MKPC) with recycled aggregates made from expanded glass or rubber granulate from tires. The thermal properties of these lightweight mortars were assessed through experimental testing. Glass fibers material was assumed as insulating filler for the first case study. Cellulose insulation was suggested as a filling material for the hexagonal cells of the second case study. The parametric models were analyzed using FEM simulations, demonstrating the potential of combining 3D printing technology with recycled materials. In fact, one configuration for each printing admixture for each case study reached the thermal transmittance limit for the predetermined climate zone (**Chapter 6**).

Application 3 is dedicated to the implementation of the methodology with the combined analysis of thermal performance and environmental impacts in the step concerning performance simulation. Therefore, this application explores the actual sustainability of 3D printed building products. In particular, this application examines the thermal properties and environmental impacts of three additive manufacturing technologies for constructing building envelopes: large-scale 3D printing (scenario 1), 3D printing for prefabrication (scenario 2), and FDM-based formwork techniques (scenario 3). The study explores how these three approaches can be applied to create different configurations of building envelopes with specific performance targets. The iterative design and thermal analysis methodology was implemented with a single automated algorithm that closely links configuration and thermal analysis. The phase of performance study of the adopted method, in addition to thermal analysis, assesses the environmental impact of the envelope components on development. An LCA analysis has been conducted to explore the sustainable potential of cited 3D printing technologies. This comprehensive study provides valuable insights into the sustainability and performance of different production technologies making manufacturing technology a parameter to be evaluated in terms of sustainability in the building component development process. In all scenarios, concrete production is one of the most environmentally impactful phases, contributing up to 95% of the total environmental impacts. Generally, increasing the number of infill sinusoids and wall thickness leads to higher material use and environmental impacts. Thus, thin walls made through pre-fabrication and FDM-based formwork techniques could improve sustainability by reducing raw concrete impacts while maintaining thermal performance. 3D printers used for monolithic construction and prefabrication have low energy consumption and high productivity. The energy and resource consumption to operate these 3D printers is minimal (about 1% of the total footprint). These printers also appear to be the most sustainable options when comparing similar geometric configurations. FDM-based formwork significantly raises environmental impacts due to raw PLA production and machine energy use. Scenario 3 impacts could be reduced by using recycled materials and sustainable energy sources, potentially bringing its impact closer to those of the other two scenarios. These findings offer valuable insights for both researchers and construction companies looking to improve the sustainability of their 3D concrete printing processes. Together with the LCA, these results will offer a comprehensive decision-making tool for adopting 3D printing technologies in construction (**Chapter 7**).

Finally, experimental work was conducted concerning the development and prototyping of an envelope system consisting of cementitious elements to precast with 3D printing. Specifically, the work was conducted in response to the last two research questions. A preliminary phase focused on modifying a cementitious mixture to improve its performance according to the printing requirements. In addition, regarding the optimization of geometry considering printing requirements, 3D printing tests were conducted to adapt the initial geometry. In the end, a full-scale element was prototyped. The employed cementitious mixture is composed of GeoCalce® Tough with a water-binder ratio of 12.00% and 1.00% of additives. Compared to the initial model, the internal geometry has been subdivided into smaller cells. This made it possible to avoid the formation of long, slender walls by creating internal baffles for self-supporting. In particular, the pocket is divided by a triangular wall, which in the printing phase made it possible to support the load of the fresh mortar layers of the sloping wall. In addition, geometry is designed to create a continuous path during extrusion to improve print quality (**Chapter 8**).

In conclusion, the work conducted led to the development of a wide-ranging methodology to support the design of prefabricated building components with 3D printing that can implement the decision-making process to achieve the performance of specific content. This approach can maximize the opportunities offered by this technology, especially from a customization point of view. An already-designed system can be easily modified and implemented in specific contexts and for particular requirements. All this enables row material to be used only when required and in an optimized way in favor of sustainability. In addition, the method can involve a preliminary phase of evaluation and selection of recycled materials. Although the applications focus on thermal performance and environmental impact, the methodology can bring together different types of features that the final products are required to achieve. This approach allows also the optimization of structural, acoustic, and other properties by balancing the parameters of the corresponding simulation models.

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11. LIST OF FIGURES

12. LIST OF TABLES

13. LIST OF ABBREVIATIONS

3DCP	3D Construction Printing
ACLab	Advanced Ceramics R&D Lab
AEC	Architecture, Engineering, and Construction
ASTM	American Society for Testing and Materials
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CC	Contour Crafting
CED	Cumulative Energy Demand
DM	Ministerial Decree
FA	Fly Ash
FDM	Fused Deposition Modeling
FEM	Finite Element JMethod
GWP	Global Warming Potential
IAAC	Institute for Advanced Architecture of Catalonia
IPCC	International Panel on Climate Change
ISARC	International Symposium on Automation and Robotics in Construction
ISO	International Organization for Standardization
KDP	Potassium Dihydrogen Phosphate
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MCA	Multiple Correspondence Analysis
PLA	Polylactic Acid
PP	Polypropylene
SF	Silica Fume
SOM	Skidmore, Owings & Merrill
STL	Standard Triangle Language
TAM	Twente Additive Manufacturing

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15. CURRICULUM

PERSONAL INFORMATION

STELLADRIANA VOLPE IS A CHARTERED BUILDING ENGINEER AND PHD CANDIDATE AT POLYTECHNIC UNIVERSITY OF BARI (ITALY). AFTER RECEIVING A MASTER'S DEGREE IN BUILDING ENGINEERING WITH A THESIS ON HIGH-PERFORMANCE BUILDING ENVELOPES MADE BY 3D PRINTING, SHE HAS CONTINUED TO INVESTIGATE ISSUES RELATED TO 3D CONSTRUCTION PRINTING CONSIDERING FUTURE DIRECTIONS OF SUCH TECHNOLOGY.

First name/ Surname	**Stelladriana VOLPE**
Date of birth	10/08/1996
Nationality	ITALIAN
Address	VIA GENTILE 97 BARI
Telephone	+39 3331934578
E-mail	stelladriana.volpe@poliba.it

EDUCATION AND TRAINING

Dates	6/10/2021 - current
Name and type of organisation providing education and training	Politecnico di Bari State University Via Edoardo Orabona 4 Bari
Course	Risk and environmental, territorial and building development Ph.D.
Level in national or international classification	Ph.D.
Dates	13/11/2018 – 12/11/2020

Name and type of organisation providing education and training	Politecnico di Bari State University Via Edoardo Orabona 4 Bari
Principal subjects/occupational skills covered	Construction engineering – LM-24 Design and execution of building complexes; design and execution of rehabilitation of existing building stock; design of urban planning interventions; design and execution of building bodies; planning and management of building production. Thesis titled: High-performance building envelopes made by 3D printing.
Title of qualification awarded	Master's Degree in Building Systems Engineering 110 cum Laude
Level in national or international classification	Second Level Graduate in Building Engineering

Dates	01/08/2015 – 08/10/2018
Name and type of organisation providing education and training	Politecnico di Bari State University Via Edoardo Orabona 4 Bari
Principal subjects/occupational skills covered	Building Sciences – L-23 Mathematics, geometry, general physics, general chemistry, integrated with foundational disciplines of the so-called Building Sciences, such as the physics of buildings, chemistry and physics of building materials and their behavior in operation, Construction Science and Technology for structural aspects and other disciplinary

	fundamentals in the area of technology and economics, as well as the basic elements of hydraulics Thesis titled: Innovative materials made by 3D printing.
Title of qualification awarded	Degree in Building Engineering 110 cum Laude
Level in national or international classification	Bachelor's in Building Engineering
Dates	25/06/2014
Name and type of organisation providing education and training	GOETHE INSTITUT
Principal subjects/occupational skills covered	German Language Certificate
Title of qualification awarded	GOETHE-ZERTIFIKAT B2
Dates	09/2010 - 06/2015
Name and type of organisation providing education and training	Liceo Classico Statale Socrate Classical High School Via S. Tommaso D'Aquino 4 Bari
Principal subjects/occupational skills covered	Italian, Latin and classical Greek language and literature; English language and literature; German language and literature; philosophy and history; mathematics; science.
Title of qualification awarded	Classical high school diploma

Level in national or international classification	Upper secondary education

WORK EXPERIENCE

Dates	22/07/2024 – current
Name and address of employer	Comando provinciale dei Vigili del Fuoco di Brescia Via delle Scuole 12, Brescia
Type of business or sector	Corpo Nazionale dei Vigili del Fuoco
Occupation or position held	Ispettore Antincendi
Dates	23/04/2023 – 02/07/2023
Name and address of employer	Faculdade de Engenharia da Universidade do PortoRua Dr. Roberto Frias, 4200-465 Porto, Portogallo
Type of business or sector	University
Occupation or position held	PhD visiting period
Main activities and responsibilities	Prototyping of precast envelope components with 3D printable cementitious materials
Dates	28/05/2021 – 28/10/2021
Name and address of employer	Politecnico di Bari State University Via Edoardo Orabona 4, Bari
Type of business or sector	University

Occupation or position held	Collaborazione coordinata e continuativa
Main activities and responsibilities	Specifica di servizi innovativi relativi alle connessioni città – porto di Bari
Dates	30/06/2021 – 31/08/2021
Name and address of employer	Faculdade de Engenharia da Universidade do Porto Rua Dr. Roberto Frias, 4200-465 Porto, Portogallo
Type of business or sector	University
Occupation or position held	Erasmus+ Traineeship
Main activities and responsibilities	Study and analysis of literature regarding 3D printing technology applied to the construction sector
Dates	28/11/2020 – 29/06/2021
Name and address of employer	EASY HOUSE SYSTEM S.R.L.S Via Cancello Rotto 3C, Bari
Type of business or sector	Engineering and Innovative Construction Company
Occupation or position held	Collaboration
Main activities and responsibilities	Collaboration in extraordinary maintenance projects; survey and graphic rendering of buildings with CAD software; development of BIM models; metric calculations; compositional and technological research of innovative modular components for prefabricated systems. Design of interventions for the recovery or restoration of exterior facades of existing buildings. Design of energy efficiency

interventions. Participation in design competition for the redevelopment of public spaces in Piazza Castello, Taranto.

Dates	04/05/2018 – 05/06/2018
Name and address of employer	Studio Tecnico Ing. Giulitto Giuseppe Via Trento 5, Bari
Type of business or sector	Engineering firm
Occupation or position held	Internship
Main activities and responsibilities	Participation in technical activities of study, design and construction site.

PUBLICATIONS

Life cycle assessment of building envelopes manufactured through different 3D printing technologies 2024
Iacopo Bianchi, **Stelladriana Volpe**, Francesco Fiorito, Archimede Forcellese,
Valentino Sangiorgio. 2024. "Life cycle assessment of building envelopes manufactured through different 3D printing technologies" Journal of Cleaner Production, volume 440, pp. 140905.

Blocchi stampati in 3D con materiale riciclato per edifici innovativi 2023
Stelladriana Volpe; Valentino Sangiorgio; Andrea Petrella; Michele Notarnicola; Humberto Varum; Francesco Fiorito. 2023 "Blocchi stampati in 3D con materiale riciclato per edifici innovativi" Colloqui.AT.e 2023 – In

transizione opportunità e sfide per l'ambiente costruito, Bari 14-17 giugno 2023.

3D printed concrete blocks made with sustainable recycled material 2023
Stelladriana Volpe; Valentino Sangiorgio; Andrea Petrella; Michele Notarnicola; Humberto Varum; Francesco Fiorito. 2023. "3D printed concrete blocks made with sustainable recycled material" VITRUVIO - International Journal of Architectural Technology and Sustainability, 8(special issue), pp. 70-83.

Overview of 3D construction printing and future perspectives: a review of technology, companies and research progression 2022
Stelladriana Volpe; Valentino Sangiorgio; Francesco Fiorito; Humberto Varum. 2022. "Overview of 3D construction printing and future perspectives: a review of technology, companies and research progression". Architectural Science Review.

Material re-use in 3D printed building components 2022
Stelladrianna Volpe; Sangiorgio Valentino; Andrea Petrella; Michele Notarnicola; Humberto Varum; Fiorito Francesco. 2022. "Material re-use in 3D printed building components". Proceedings of the X th edition of the ReUSO - Documentation, Restoration and Reuse of Heritage, Porto, Portugal 2-4 November 2022.

Design of an efficient 3D printed envelope supported by parametric modelling 2022
Stelladriana Volpe; Valentino Sangiorgio; Francesco Fiorito. 2022. "Design of an efficient 3D printed envelope supported by parametric modelling". Colloqui.AT.e 2022 – Memoria e Innovazione, pp. 1427-1438, Genova 7-10 settembre 2022.

Preparation and characterization of novel environmentally sustainable mortars based on magnesium potassium phosphate cement for additive manufacturing AIMS Materials Science 2021
Stelladriana Volpe; Andrea Petrella; Valentino Sangiorgio; Michele Notarnicola; Francesco Fiorito. 2021. "Preparation and characterization of novel environmentally sustainable mortars based on magnesium potassium phosphate cement for additive manufacturing AIMS Materials Science". AIMS Materials Science, volume 8, Issue 4: pp. 640-658.

Building Envelope Prefabricated with 3D Printing Technology 2021
Stelladriana Volpe, Valentino Sangiorgio, Andrea Petrella, Armando Coppola, Michele Notarnicola, and Francesco Fiorito. 2021. "Building Envelope Prefabricated with 3D Printing Technology" Sustainability 13, no. 16: 8923.

PERSONAL SKILLS AND COMPETENCES

Mother tongue	Italian

Other languages	
	English
Reading	excellent
Writing	excellent
Speaking	excellent
	German
Reading	good
Writing	good
Speaking	good

Social skills and competences	Good interpersonal skills developed: in the academic field through collaboration in group projects during the training period; in the field of research and development of scientific publications by collaborating with co-authors; in the field of experience abroad during which we related with a multicultural environment; in the work field through close collaboration with colleagues for the development of projects of extraordinary maintenance, recovery, energy upgrading and surveying activities; in the field of participation in the design competition for the redevelopment of public spaces in Piazza Castello, Taranto during which we collaborated in a team of several professionals.
Organisational skills and competences	Good organizational skills particularly developed during the university years through various group project experiences. also applied and developed competence in completing assigned work on time during the work period.
Technical skills and competences	**CAD and BIM**

Autodesk Navisworks / Good skills in Autodesk Robot Structural
Analysis / CAD and BIM software: Autodesk Autocad, Autodesk Revit and Families editing

Energy simulation

Design Builder / Icaro / Acoustic insulation Analysis ACCA SuoNus / MASTER CLIMA (MC11300)

Metrical estimate

Primus - Acca
Software / Suite Mosaico

G.I.S.

Q-GIS

Graphic Design

Adobe Photoshop
Adobe InDesign

Office

Office Suite (Word Excel PowerPoint etc.)

Statistical Computing

XLSTAT
R

Abstract

To date, the construction industry is globally among the most impactful on the environment. A look into the past may lead to questioning about how housing systems have been transformed and how to cope with current critical issues. A common factor in past architectural styles for each location has always been the adaptation to the climate and the natural environment. As a result, the architectural landscape is unique to each region of the world. This trend was reversed when standardized construction techniques replaced traditional and local methods. The consequences of this technological standardization are among the causes of the current significant environmental impact of the construction sector. 3D printing is a production technology, already established in other industrial sectors, that proves to be one of the most promising technologies to innovate the construction sector. Among the different potentials, 3D printing technology offers a greater degree of geometrical freedom that could allow for a renewed connection between architectural forms and the surrounding environment.

The primary aim of this thesis is to explore the possibilities that 3D printing offers to the construction industry. Specifically, by studying the evolution of 3D printing in construction both from a market and scientific research perspective, the current limitations to the widespread applicability of 3D printing for building construction have been highlighted. To overcome some of these limitations, this study proposes a methodological approach to support the design of building components, based on the parameterization of digital models and the iterative analysis of their performance. This allows for the creation of adaptable building elements suitable for different boundary conditions and prefabricated using 3D printing technology. The methodological approach has been employed in various applications and related case studies that specifically implement the basic methodology regarding aspects of thermal performance, recycling of raw materials, sustainability, and the environmental impact of construction processes. Finally, the approach was adopted for the development and prototyping of an envelope system made of prefabricated cementitious elements using 3D printing.

On the cover: 'Building construction industry evolution

Abstract

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