A Cost Model for Additive Manufacturing in Construction

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Abstract. The construction industry faces several challenges every day, which are pushing this sector to start a process of innovation. In this contest, Additive Manufacturing (AM) represents an innovation and digitalization opportunity; on this basis, this work will focus on an assessment of AM as an enabling technology for this industry, especially from a cost perspective. In particular, since there is not yet a suitable cost model for AM in construction, a cost model will be developed to assess whether it is cost effective to use 3D printing in the building industry. The results obtained from the application of the cost model on a case study are very promising as they open up new avenues for considering 3D printing as a valid alternative to traditional construction methods.

1. Introduction

The construction sector has recently embarked on a process of innovation aimed at countering its traditional challenges, i.e., lack of a skilled workforce, lack of safety during construction [1] working in harsh environments, production of large amounts of waste material [2], lower productivity rate compared to other industrial sectors [3]. This sector is responsible for 38% of global greenhouse gas emissions [4], and consume a very significant amount of raw materials, accounting for 50% of global steel demand [5]. New challenges have emerged during the last two years, characterized by the Covid-19 pandemic, like the vulnerability of global supply chain with consequent supply shortages of key materials and rising wholesale prices [1]. Digital technologies, such as 3D printing, autonomous construction, or prefabrication, robotics, digital-twin, artificial intelligence, and analytics, supported by Building Information Modeling (BIM) have the potential to help fighting traditional and pandemic induced challenges [1], [6]. The trend of technology adoption seems to have reversed course, accelerated precisely by the Covid-19 pandemic; in particular, great opportunities arise from robotics for repetitive tasks such as brick laying, road paving, and 3D printing of building materials [6].

For these reasons, this article deals with the possibilities of innovation and digitization in construction, with a focus on Additive Manufacturing (AM), also known as 3D printing, which is defined as *''the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining''* (ASTM Standard).

Although the first applications of AM in the 90s were mainly related to rapid prototyping for the manufacturing industry, today this technology is applied in the production of end products in many sectors such as biomedical, aerospace, aeronautics and automotive. In this context, the construction sector has also been affected by the spread of 3D printing, with a particular acceleration in recent years as demonstrated by the appearance of the new cluster *"3D printing, modularization and robotics"* in the map of the global construction technology industry ecosystem developed by [6].

AM allows to produce geometrically complex structures, to vary materials within a component, and to automate the construction process from a digital model [7]. Additional benefits include reduced material waste (up to 30%), reduced resource requirements and lower CO_2 emissions throughout the product life cycle [8]. The FoamWork technology developed by ETH Zurich, for example, allows to create a precast concrete slab that uses 70 per cent less material, and, if used ad large scale, could reduce the carbon emission of cement [4].

However, AM adoption in construction is also characterised by weaknesses including the high cost of large-scale 3D printers, the precision and quality of final results that may not live up to expectations and would require post processing treatments, the lack of regulations and standards that have yet to be adapted to this technology [8], general industry scepticism [9], limitation in the realization of large-scale buildings and constraints in the choice of printable materials [10]. Nevertheless, a possible solution for limiting the costs of the application of 3D printing to high rise buildings could be the use of smaller robots and printers for the construction of a set of high value components, as shown by the DFAB HOUSE demonstrator [11].

Cost-efficiency has been recognized as a driver for 3D printing but often the cost calculation does not take into account all the necessary components [12]. In spite of this, high initial investment costs (equipment and logistics) are indicated as important barriers to the widespread adoption of 3D printing [12], [13], [14]. Defining a cost model has been indicated as a first instrument to compare AM cost-efficiency to classical production methods and facilitating the uptake of this technology in a traditional manufacturing environment [15]. To this end, many cost models specific for AM have been developed in the manufacturing context [16]. The importance of cost models as tools, techniques, methods to predict costs is recognized by many researchers; according to [17] cost model is *"the symbolic representation of a system, expressing the content of that system in terms of the factors which influence its costs"*. For this reason, this paper evaluates the potential of 3D printing with a cost perspective, by introducing a cost model for AM in construction.

2. Research Methodology

First, a Systematic Literature Review (SLR) was conducted by interrogating the Scopus database, in order to answer the following research questions: *Which cost models are adopted in AM? Which cost models are used for 3D printing in construction?* The cost models found in literature both in manufacturing and in construction fields were analysed. Based on the results of the analysis, a cost model for 3D printing applications in construction has been introduced. Then, a test is proposed where a sample structure is imagined to be built once with traditional methods and then using AM for vertical structures. The construction costs arising from the AM were calculated through the introduced cost model, while the costs arising from the traditional construction method were determined through an analytical approach, namely Quantity Take Off (QTO). Finally, the results obtained from the case study are analysed and discussed and conclusions are drawn.

3. Systematic Literature Review

A Systematic Literature Review (SLR) was carried out by querying the Scopus database using the keywords shown in Figure 1. Several filtering criteria were applied to output articles: (1) relevance to the topic; (2) availability of paper for consultation (3) duplicate discard. The workflow is shown in Figure 1.

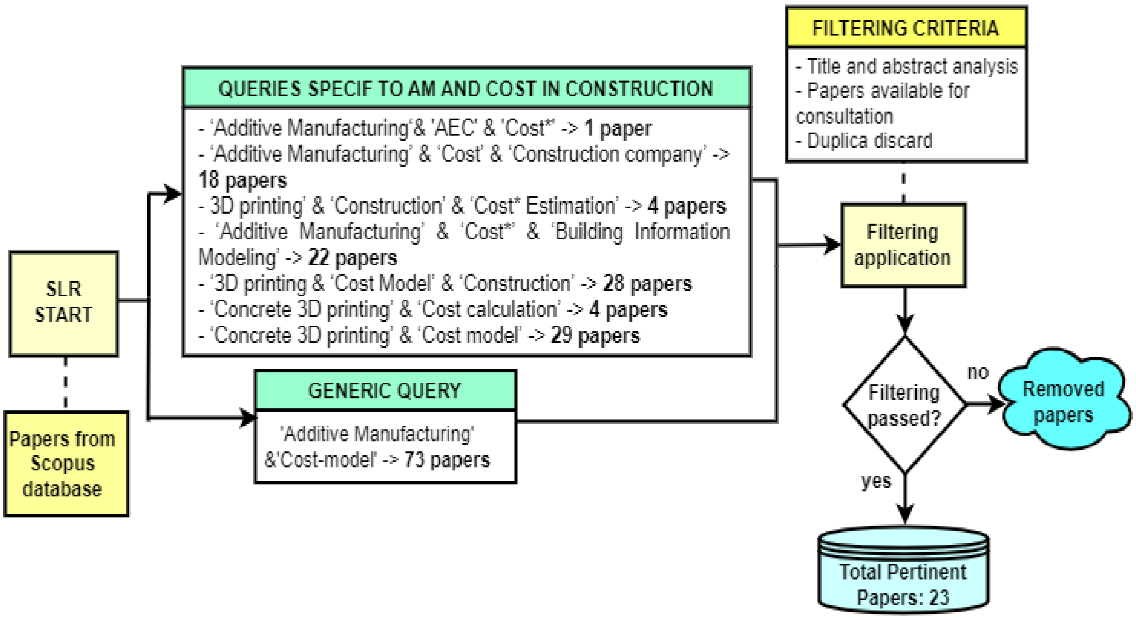

Figure 1. Workflow SLR.

The analysis of the articles related to the cost of 3D printing in construction has shown that the majority of these studies have applied a methodology to calculate the cost of the construction of a reinforced concrete wall [18], [19], [20], [21]. These studies show that the productivity and cost benefits of AM increase with the complexity of the shape of the wall. The study of Zhang et al. [18] is the only aimed specifically at defining a cost model for 3D printing in construction, proposing an activity-based cost model, i.e., based on the activities involved in the Contour Crafting process. Krimi et al. [20] focused on confirming that the high production rate of 3D printing lowers overall construction costs. Otto et al. [21] did not include the cost of the 3D printing machine, due to the lack of availability of manufacturing and sale information for the specific device considered; so, the study was aimed at evaluating the maximum cost of the machine in order to be competitive with traditional construction method. Bataev [22] did not directly calculate the cost of 3D printing but proposes a coefficient *"showing how much the cost price of one square meter of housing is lower when using 3D printing than with traditional construction"*, demonstrating that using 3D printing technology can be *"profitable only in the mass production segment"*. Akulova and Slavcheva [23] included in the cost of a machine-hour *"the cost of depreciation, human labor costs, the replacement of high-wear parts and units of machines, for energy, maintenance, relocation and installation of machines on the construction site"*.

Although these works focus on the economic feasibility of using AM as a construction method, [18] is the only study that introduces a cost model specific to the construction sector; however, it does not consider some important cost components, such as overheads and post processing, highlighted by the cost models specific for the manufacturing sector analysed hereafter.

Indeed, from the analysis of the articles output of the query 'Additive Manufacturing' & 'Cost-model' is deduced a more structured treatment of the concept of cost modelling. Hopkinson and Dickens [24] were among the first to analyse AM costs introducing a cost model that include machine, labour, and material costs; Ruffo et al. [15] proposed an activity-based cost model with the aim to review and enhance the model of Hopkinson and Dickens. Baumers et al. [25] introduced an AM cost model, with a detailed analysis of economic and energetic aspects; the model presented is activity-based, with a distinction of direct and indirect costs. Lindemann et al. [26] proposed a model with an activity-based approach that considers four main AM activities: building preparation, building production, support removing, and post processing. Rickenbacher et al. [27] introduced a model considering pre- and post-processing steps, idle phases, and an algorithm to calculate the time fraction for each part. Schröder et al. [28] proposed an activity-based model cost that considers seven processes: design and planning, material processing, machine preparation, manufacturing, post-processing, administration and sales, control quality. Mahadik and Masel [29] proposed a cost model using the breakdown approach in which the total cost of the part is the sum of four cost components: machine, material, labour, and post-processing. Atzeni and Salmi [30] assessed the cost-effectiveness of AM as an alternative to traditional production processes by introducing a model that considers four main cost items: material, pre-processing, processing, and post-processing.

It is important to note that although the cost models analysed in some cases refer to specific AM technologies and industrial fields, the main cost components remain the same, suggesting a wider application regardless of the production process and field of application. Table 1 presents the main cost items considered in the most relevant papers analysed (the paperID is the first author of the paper if the paper has more than two authors, and all authors if the paper has only two authors).

Table 1. Cost item analysed per PaperID.

PaperID / Cost Item	Hopkinson &Dickensen	Ruffo	Baumers	Lindemann	Rickenbacher	Schröder	Fera	Mahadik	Yim	Atzeni &Salmi	Kampker	Lei Di	Krimi	De Soto	Otto	Bataev	Akulova	Zhang
	Papers from query 'Additive Manufactuing' and 'Cost-model'												Papers related to AM cost and construction					
Machine (general)	✓	✓	✓					✓	✓				✓	✓	✓		✓	
Machine set up				✓	✓	✓	✓											
Machine depration													✓					
Machine operation						✓			✓		✓							✓
Material	✓	✓	✓			✓		✓	✓	✓		✓	✓	✓	✓	✓		✓
Labour/Wage	✓	✓	✓					✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Design						✓										✓		
Pre processing				✓	✓		✓			✓	✓							✓
Processing				✓	✓	✓	✓			✓	✓							✓
Assembling					✓		✓											
Energy			✓									✓					✓	
Post processing				✓	✓	✓		✓		✓	✓							
Overheads		✓	✓			✓						✓					✓	

4. Cost model structure

Based on the results of the SLR, thus on the analysis of the cost models summed up in Table 1, a cost model for AM in construction is introduced. The model proposed is activity based, as in many of the analysed studies, following a process composed of a sequence of steps: design, transport of the machine to construction site, machine set up, machine operation, post processing. The total cost of 3D printed structure is therefore equal to the sum of design cost; transportation cost; material cost; machine cost; energy cost, that, for the purposes of this work, is included in machine cost per hour; post processing cost; wage cost, that, for the purposes of this work, is included into design cost, machine cost and post processing cost; production and administration overheads (equation (1)). Each cost item, with its respective calculation formula, is detailed in Table 2.

It was felt that the cost of the design should be made explicit due to the differences with designing structures using traditional methods, such as producing the file for the machine. Machine costs need to be explicit, as one of the major concerns for the introduction of 3D printing is the high initial equipment costs. Post-processing costs express the particularity of 3D printing to produce surfaces that require specific finishes.

$$C_{total} = C_{design} + C_{transport} + C_{material} + C_{machine} + C_{post} + C_{wage} + C_{energy} + C_{overheads} \quad (1)$$

Table 2. Item of the proposed cost model.

Item	Symbol	Formula
Design cost	C_{design}	Designer hourly cost [€/h] * Design time [h]
Transport cost	$C_{transport}$	Unit transport cost [€/km] * Distance [km]
Material cost	$C_{material}$	Unit material cost [€/kg] * Mass of material [kg]
Machine cost	$C_{machine}$	Machine depreciation cost [€] + Machine setup costs [€] + Machine processing cost [€]
Post-processing cost	C_{post}	Unit cost post processing [€/sqm] * Quantity [sqm]
Wage cost	C_{wage}	Hourly operator cost [€/h] * Operator's working hours [h]
Energy cost	C_{energy}	Unit cost of energy [€/kWh] * Energy consumed [kWh]
Overheads	$C_{overheads}$	15-20% of total cost

5. Application and results

The application part of this work is aimed at comparing the construction costs of the vertical structures of a sample building calculated under two different hypotheses: (i) construction with a conventional approach and (ii) construction using AM. The sample building is a mixed construction of load-bearing walls and pillars, located in Lecce (Apulia, Italy) and consisting of a ground floor and a first floor, modelled in Revit (v. 2021) (Figure 2 and Figure 3). Construction costs resulting from AM are calculated by means of cost model (1), while the costs resulting from conventional approach are determined through Quantity Take Off.

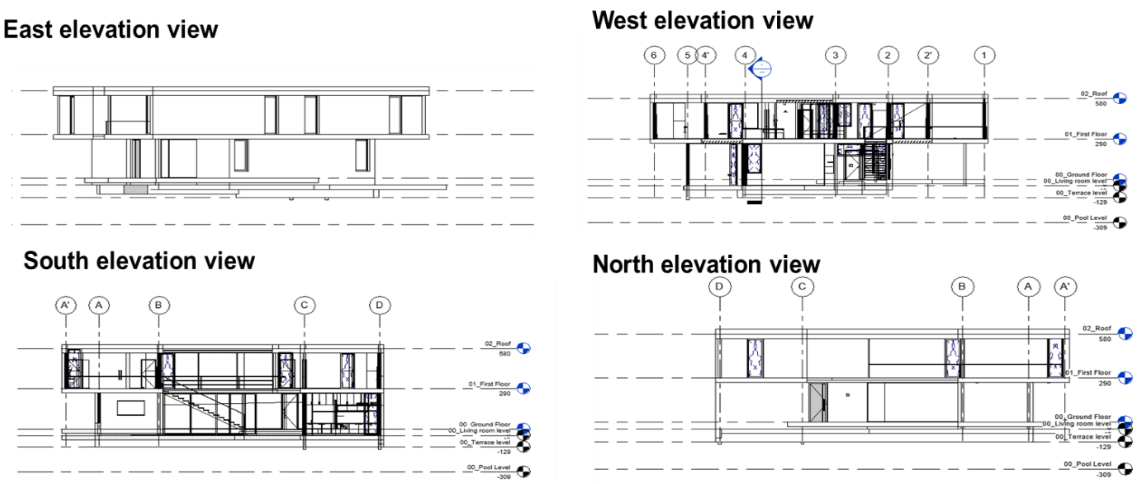

Figure 2. Elevation views.

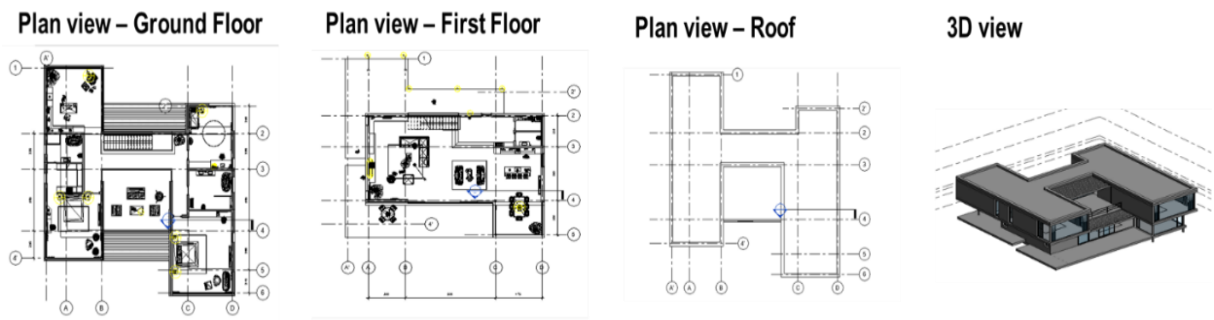

Figure 3. Plan and 3D views.

5.1. AM approach: cost model implementation

Cost model (1) is applied with the aim of calculating the AM construction costs of the vertical structures of the above-mentioned construction. The BOD2 (short for Building on Demand) printer, from the Danish company COBOD International, has been taken as the reference. BOD2 (Figure 4), described by the manufacturer as the fastest and most flexible 3D concrete printing globally, is an improved version of the printer which was used to 3D print the first building in Europe, the BOD.

Figure 4. BOD2 3D printer (courtesy of COBOD International).

The specifications of the printer have been obtained from the manufacturer and are listed in Table 3.

Table 3. BOD2 specifications.

BOD2 SPECIFICATIONS	
Max printing length	As long as you like
Max printing width	14.6 m
Max printing height	8.1 m
Max printing speed	Up to 1000 mm/s (1 meter/s)
Layer height	Up to 40 mm
Layer width	Up to 300 mm
Material flow	< 3.6 m^3/h
Max aggregate size	< 10 mm
Printer setup time	4-6 hours
Printer takedown time	3-4 hours
Manning	2 operators
Power supply	32 A, 400 V, 3 phases

Based on cost model (1), each cost item has been determined:

1. **Design cost** has been determined by multiplying the design time [h] by the hourly cost of the designer [€/h]. Assumptions have been made; it has been supposed that the average design time is half a working day (i.e., 4 h) and that the hourly wage of one design engineer is 50 €/h (Italian cost reference, 'Decreto Ministeriale 17 June 2016' [31]).
2. **Transport cost:** transport of printing equipment from warehouse to construction site, determined by multiplying the average fuel consumption by the unit cost of fuel [€/l], assuming an average distance to be covered by truck of 100 km.
3. **Material cost** has been evaluated by multiplying the mass of the material used [kg] by the unit cost per kilogram of the material [€/kg], obtained from the manufacturer of the printer. The mass of concrete has been determined according to equation (2):

$$\rho_{concrete} = \frac{m_{concrete}}{V_{concrete}} \tag{2}$$

- $\rho_{concrete}$ is the density of the printing concrete, assumed equal to 2.250 kg/m^3;
- $m_{concrete}$ is the mass of the printing concrete;
- $V_{concrete}$ is the volume of the printing concrete, determined using Revit 2021's Abacus function, which provides a bill of quantities of load-bearing walls, internal walls, and pillars.

4. **Machine cost** has been calculated as the sum of three cost items:
   - **Machine depreciation cost** determined assuming a useful life of the asset of 5 years.
   - **Machine set up cost** calculated by multiplying the setup time [h] by the operator cost per hour [€/h] by the number of operators. According to the printer's data sheet the average set-up time is 4-6 hours and the number of operators required to manage the machine is 2. It is assumed an hourly cost of a specialised operator of 50 €/h (Italian cost reference, 'Decreto Ministeriale 17 June 2016' [31]);
   - **Machine processing cost** has been determined by multiplying the build time [h] by the machine hourly cost (assumed equal to 50 €/h). The build time (equation (3)) has been obtained by dividing the total cubic metres of vertical structures, determined according to Revit 2021's Abacus function, by the material flow rate of the BOD2 printer, equal to 3.6 m^3/h (Table 3).

$$\text{Build time} = \frac{\text{Total volume}}{\text{Material flow}} \tag{3}$$

5. **Post processing cost** has been determined by multiplying the unit cost of the post processing activity (e.g., [€/m^2]) by the quantity (e.g., [m^2]). Unit costs (including labour) have been selected from the Apulia Region Price List, while quantities have been obtained using Revit 2021's Abacus. According to the Price List the post processing activities considered are: *"Reinforcing of masonry to be plastered, carried out with brick flakes and cement mortar, to even out irregularities and flattening [...]"* (17.3 €/m^2) and "*Supply and application of smooth plaster, for interiors and exteriors"* (17.2 €/m^2 for exterior surface and 16 €/m^2 for interior).
6. **Production and administration overheads**, that include**,** for example, auxiliary equipment costs (related to scaffold, crane, formwork, etc.), facility rent, commissions, office supplies, have been calculated by considering a percentage of the total cost (15% of the total cost).

Results of the cost model application show that the cost items with the greatest influence are material (37.50 %), post-processing (30.73%) machine (18.31%) and overheads (13.04%), while the impact of design and transport activities are negligible; this results in a total cost of about 64.300 €. The cost items and their impact are represented in Figure 5 with a bar chart.

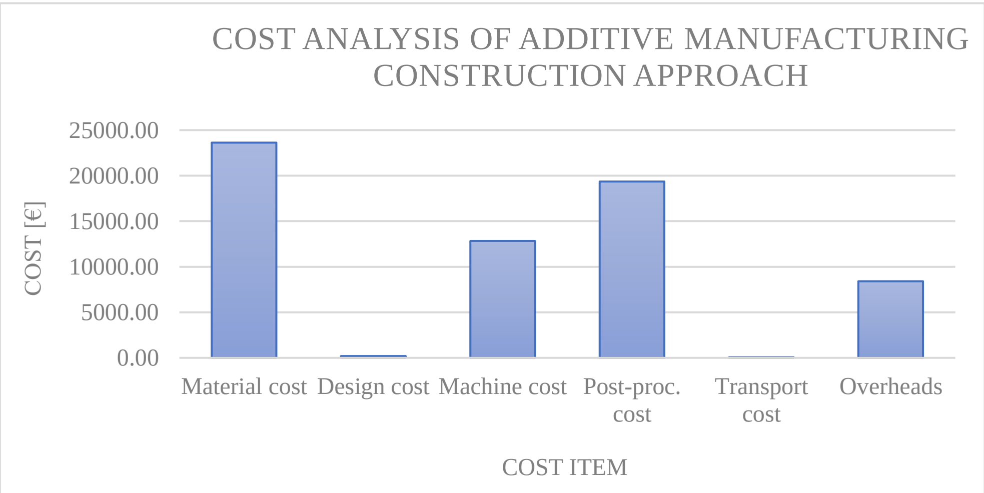

Figure 5. Cost analysis of Additive Manufacturing approach.

5.2. Traditional approach: QTO implementation

With regard to traditional construction method, construction cost, C_c, has been calculated through an analytical approach, i.e., Quantity Take Off (QTO) (equation (4)):

$$C_c = \sum_i q_i * p_i \quad (4)$$

where q_i (e.g., [m^2] or [m^3]) is quantity of the i-th work while p_i is the unit price (e.g., [€/m^2] or [€/m^3]) of the i-th work [32]. The quantity of the i-th work has been determined using Revit 2021's Abacus function while the unit price of the i-th work has been taken from the Apulia Region Price List. We proceeded calculating the cost of supply and installation of:

1. **Load bearing walls**: the reference thickness is 35 cm, and the total square footage of the masonry is 266.85 m^2.
2. **Internal walls**: the reference thicknesses are 10 cm and 20 cm, and the total square footage of the walls is 117 m^2.

It is assumed that both load bearing and internal walls are realised using brick. According to the Apulia Region Price List we refer to "*Supply and installation of straight masonry for foundation and/or elevation structures […]*" (132.3 €/m^2) and to "*Supply and application of smooth plaster, for interiors and exteriors […]*", (17.2 €/m^2 for exterior surface and 16 €/m^2 for interior).

3. **Pillars**: the reference dimension is 16x16 cm. The number of pillars and their size is small because the house is mainly of load-bearing masonry. It is assumed that pillars are realised using concrete. According to the Apulia Region Price List we refer to *"Supply and laying of concrete with guaranteed performance, in accordance with UNI EN 206-1 […]"* (162.91 €/m^3), to *"Surcharge for concrete poured directly from a truck mixer"* (19.12 €/m^3), to *"Supply and installation of formwork for concrete castings […]"* (27.80 €/m^2) and to "*Supply and application of smooth plaster, for interiors and exteriors […]*" (16.00 €/m^2).

The results of the QTO show a total cost of about 52.500 € allocated among load-bearing walls, internal walls, and pillars, as shown in Table 4.

Table 4. Cost for traditional construction approach.

COST FOR TRADITIONAL CONSTRUCTION APPROACH		
Structural element	**Cost of supply and installation [€]**	**Percentage**
Load-bearing walls	44163.68	84.11
Interior walls	7891.16	15.03
Pillars	455.03	0.87
TOTAL	**52509.87**	**100.00**

6. Discussion

This study analyses the potential of AM as an innovation opportunity for the construction sector, through a cost perspective, proposing the cost model (1). The implementation of (1) made it possible to estimate the construction cost for the elevation structures of a case study when using 3D printing, identifying the most influential cost items, i.e., materials, post-processing, machine, and administrative and production overheads. In a second step, it was assumed that the same vertical structures would be built using a conventional approach, calculating the resulting costs through the QTO.

From the analysis of the results, it can be stated that the construction costs resulting from the application of 3D printing (64.300 €) and those generated by a traditional construction approach (52.500 €) are comparable and not so different from each other. This is an important achievement, as its open new avenues on the possibility of considering AM as a viable alternative to traditional construction methods.

7. Conclusions, limitations, and future works

The aim of this paper was to discuss the application of AM technologies in construction, proposing a cost model as an instrument to facilitate the assessment of cost-effectiveness of 3D printing in the building industry as a viable alternative to conventional construction method.

This work first briefly describes the current challenges of the construction sector and the low level of adoption of digital technologies, including 3D printing. Afterwards, the results of an SLR have been presented, with a map of the main cost models proposed in the literature for AM. The proactive part of the work aimed to develop a cost model for AM in construction. In the proposed model, the total cost is divided between material, design, wage, energy, machine, post processing, production and administration overheads, and transport costs. The testing part was carried out through a case study involving a Revit 2021 model of a construction, located in Lecce. Construction costs of the elevation structures of the house were calculated assuming two different approaches for the construction: AM and traditional technologies, by applying the cost model (1) and QTO respectively.

The results of the case study show that the construction cost of 3D printing is higher, but not by much compared to that of the traditional approach; an increase that in any case can be justified by the numerous advantages that can be obtained through AM: no limits to geometric complexity, automation of the construction process, reduced resources use, material waste and CO_2 emissions throughout the product life cycle. These elements become more relevant when put in context with the current critical situation in the building industry, giving further emphasis to the spread of 3D printing.

This research limited the application of the cost model to a single, local case study, a cost calculation based on a regional price list and the reference to a single fixed design alternative; therefore, a future step will be the simulation of case studies in other locations. The model will be also validated asking the opinion of experts of the field.

This research could be also improved in the future by (1) observing the use of 3D printing equipment in a real construction site, (2) taking into account technological advances in 3D printing, like new printers, perhaps with higher performance and more affordable costs and (3) 3D printing application to foundations, horizontal structures, and finishes.

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