*sustainability*

MDPI

*Article*

# 3D-Printed Blocks: Thermal Performance Analysis and Opportunities for Insulating Materials

**Tullio de Rubeis**

Department of Industrial and Information Engineering and Economics, University of L'Aquila, 67100 L'Aquila, Italy; tullio.derubeis@univaq.it; Tel.: +39-0862-434342

**Abstract:** The building energy balance is strongly influenced by the heat transmission losses through the envelope. This justifies the growing effort to search for innovative and high-performance insulating materials. The 3D printing process, also known as additive manufacturing, is already used in various industrial applications thanks to its ability to realize complex structures with high accuracy. It also represents an emerging and still poorly explored field in the world of "building physics". The aim of this work is to present the design, realization, and analysis phases of a 3D-printed thermal insulating block. The performance analysis of the block was performed via theoretical and experimental approaches. The testing phase was conducted using a Hot Box specially built for this purpose, which allowed to have known, repeatable, and steady thermal conditions. The experimental phase, based on the infrared thermography technique and heat flow meter method, allowed a preliminary evaluation of the 3D-printed block performance. Moreover, to implement the concept of circular economy, the internal cavities of the block were filled with different recovered waste materials: polystyrene and wool. The results obtained have shown, although preliminarily, the potential of additive manufacturing in the field of insulating materials.

**Keywords:** 3D printing; additive manufacturing; insulating materials; sustainable materials; hot box analysis; infrared thermography; heat flux meter

check for updates

**Citation:** de Rubeis, T. 3D-Printed Blocks: Thermal Performance Analysis and Opportunities for Insulating Materials. *Sustainability* **2022**, *14*, 1077. https://doi.org/10.3390/su14031077

Academic Editor: Cinzia Buratti

Received: 24 December 2021
Accepted: 15 January 2022
Published: 18 January 2022



## 1. Introduction

In the global scenario, the building sector represents one of the main contributors to the final energy consumption, preceded only by the industrial and transport sectors. In 2019, the final energy consumption of the residential sector accounted for about 21% of the total, namely about $87.78 \times 10^6$ TJ [1]. Despite the numerous energy policies implemented in Europe, adopted by the different member states, greenhouse gas emissions have more than doubled since 1970 [2]. Continuing with current policies, projections to 2050 foresee $CO_2$ emissions substantially unchanged from current values, as predicted by the "*Stated Policies Scenario*" described in [3]. Therefore, to reach the ambitious scenario of "*Net Zero Emissions*" by 2050, needed to cope with climate changes [4], the efforts to find new solutions with a high energy impact must be further increased, even in the residential sector. In this context, Additive Manufacturing (AM), which is still an emerging and poorly explored field [5], could be very effective in expressing its potential among the possible energy efficiency measures.

As of today, there is a growing number of AM applications in the field of construction engineering, potentially able to overturn the commonly accepted approaches to produce thermal insulating panels. In fact, there is a nascent research activity focused on 3D printing (3DP) and the search for elements with complex geometries in the field of building construction, commonly considered a low-tech industry compared to other sectors that have significantly increased their technological content [6].

In particular, the state of the art [7] shows that 3DP is still in a nascent stage and that the efforts made are mostly addressed to printability and structural capacity of the blocks produced. However, a significant knowledge gap can still be found in the study of the

3D-printed blocks thermal behavior, despite some very recent examples published in the scientific literature.

He et al. [8] developed a modular 3D-printed concrete vertical green wall system, going so far as to build a prototype commercial building in China and demonstrating energy savings (−9.12% of annual consumption) and thermal comfort potential compared to Chinese standards.

In the work proposed by Grabowska and Kasperski [9], multilayer materials with quadrangular, hexagonal, and triangular closures are designed and 3D printed. Thermal analysis of the blocks, based on a specially developed mathematical model, showed promising results for quadrangular and hexagonal structures, obtaining thermal conductivity values of 0.0591 W/(m·K).

An interesting experimental study, carried out to analyze the thermal performance of 3D-printed blocks with different internal structures, is proposed by Mihalache et al. [10], who evaluated the response and, thus, the thermal performance of different blocks by varying the thermal stress power and the thickness of the 3D-printed blocks.

Sarakinioti et al. [11] presented the results of the SPONG3D project to develop a 3D-printed panel that integrates insulation and heat storage properties in a complex single-material geometry.

The thermal and mechanical performances of a 3D-printed macroencapsulation method for Phase Change Materials (PCMs) are presented by Maier et al. [12]. The authors used two types of cement-based mixtures with different densities and analyzed the performance of the samples by Hot Box measurements. The obtained results showed that the 3D-printed macroencapsulated specimens provide the best thermal performance.

In this context, it is interesting to explore an emerging and high potential field such as additive manufacturing. New approaches can be defined to make thermal insulating blocks, able to increase the thermal resistance of buildings opaque elements, by reducing the transmission heat losses.

In this paper, a novel 3D-printed thermal insulating block is presented.

The main objectives and novelties introduced by this work are:

- to propose a new 3D-printed block to be used as thermal insulation of building walls, also considering criticalities and potentials related to its realization;
- to analyze the thermal performance of the prototype 3D-printed block via theoretical and experimental approaches (by means of InfraRed Thermography (IRT) technique and Heat Flow Meter (HFM) method in Hot Box apparatus);
- to evaluate the thermal performance of the 3D-printed block by filling its air cavities with waste materials, thus implementing the concept of circular economy.

In particular, the 2D and 3D design phase of the block and its realization phase are described. Then, the thermal performance analysis of the block is performed via theoretical and experimental approaches. The experimental analysis of the 3D-block is carried out considering stationary, controlled, and repeatable thermal conditions. To this aim, a Hot Box has been specifically constructed. Moreover, exploiting the air cavities of the block and implementing the circular economy concept, different waste materials were selected to fill the air cavities: polystyrene and wool.

The work is divided into four sections: after the introduction (Section 1), and Section 2 describes the methodology used and the experimental phase, i.e., measuring instruments and setup. Section 3 discusses the main results obtained, while the conclusions are presented in Section 4.

## 2. Materials and Methods

With the deployment of BIM (Building Information Modelling) and 3DP, the construction industry is embarking on a necessary digitizing path, already widely implemented in other industries, such as manufacturing.

Generally, the realization of 3D-printed blocks can be carried out with different printing methods and with different materials. Plastics are generally used: (i) thermoplastics, widely employed, can go through numerous melting and solidification cycles allowing, therefore, a reversible process without chemical bonds; (ii) thermoset plastics, also known as “thermosets”, remain in a permanent solid state after polymerization, creating chemical bonds.

The 3DP processes are numerous (e.g., binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization), but those considered most interesting and most used for the purposes of this work are:

- Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF) is an additive manufacturing technology that involves the melting and extrusion of thermoplastic filaments. The filaments are then deposited “layer upon layer” by the extrusion nozzle in the printing area, thus creating anisotropic objects. The materials most used for FDM printing are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). Currently, FDM is the most popular printing process due to its fast prototyping and relatively low cost.
- Stereolithography (SLA or SL), the first 3DP process, is a technique based on a photochemical process, in which light is used to create polymers. It is still widely used as it allows to print isotropic objects, with high resolution and precision. Resin is generally used for SLA 3DP, such as standard, clear, and engineering (though, durable, heat resistant, flexible, and rigid) resin.
- Selective Laser Sintering (SLS) employs a high-power laser to melt small particles of powder material, resulting in robust, functional objects with complex geometries that are generally isotropic. The most used material for SLS is lightweight, strong and flexible nylon.

In all cases, the printing of a 3D object requires the creation of a 3D model to be subsequently exported in an STL (Standard Tessellation Language) file, which is the standard file format containing geometric information of the 3D object. Subsequently, through a slicing process carried out with appropriate software, the printing characteristics can be assigned, including for example: print orientation, layer height, and commands for extrusion nozzle positioning [13].

### 2.1. Methodology Employed

Based on what has been described so far, the objective of this work is twofold: (i) to design and realize the prototype of a 3D-printed block to be used as insulating material and (ii) to employ waste materials to be inserted into the air cavities of the block, in order to improve its thermal properties and implement the concept of circular economy (i.e., sharing, reusing, repairing and recycling existing materials and products as long as possible [14]).

To achieve these objectives, the methodology described in Figure 1 was applied, in which 3 operational macrophases are distinguished. The first phase—called *design phase*—allowed the 2D and 3D design of the block, using a three-dimensional modeling tool (AutoCAD Inventor®, Autodesk Inc., San Rafael - USA). Then, the design was processed through a slicer software (Creality Slicer 4.2, Creality 3D Technology Co., Shenzhen, China) to generate the G-Code and assign all the printing characteristics. Finally, the printing phase of the block was started, by means of the Creality CR-3040 PRO 3D printer.

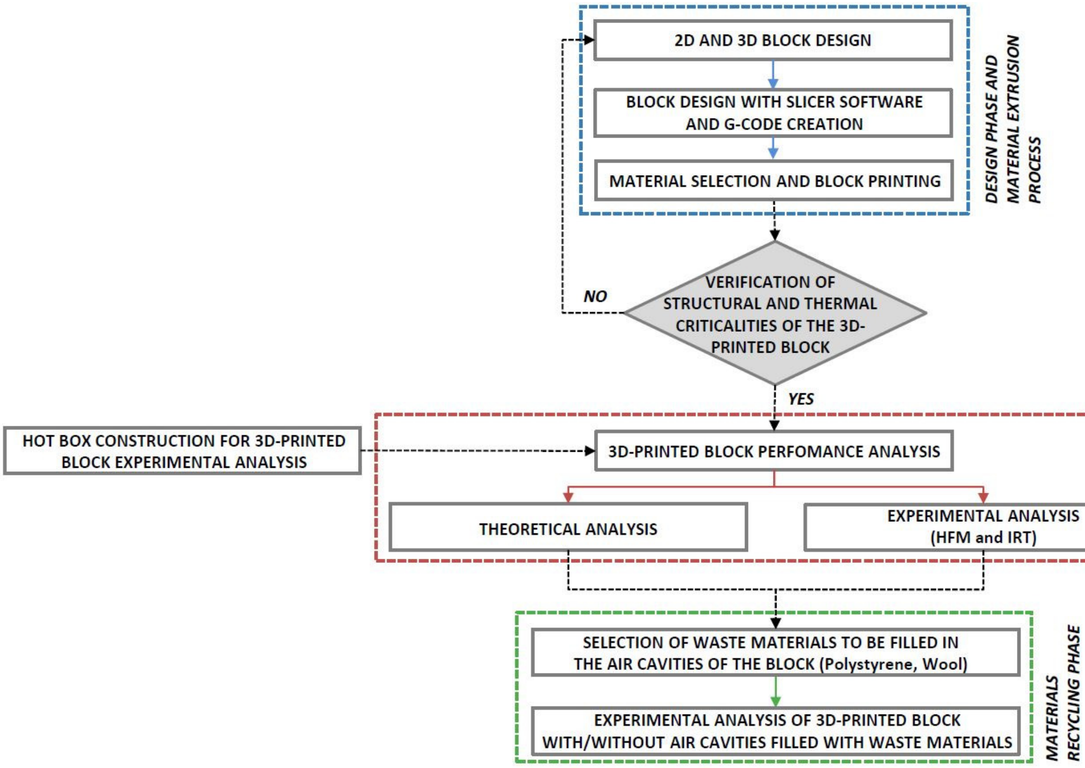


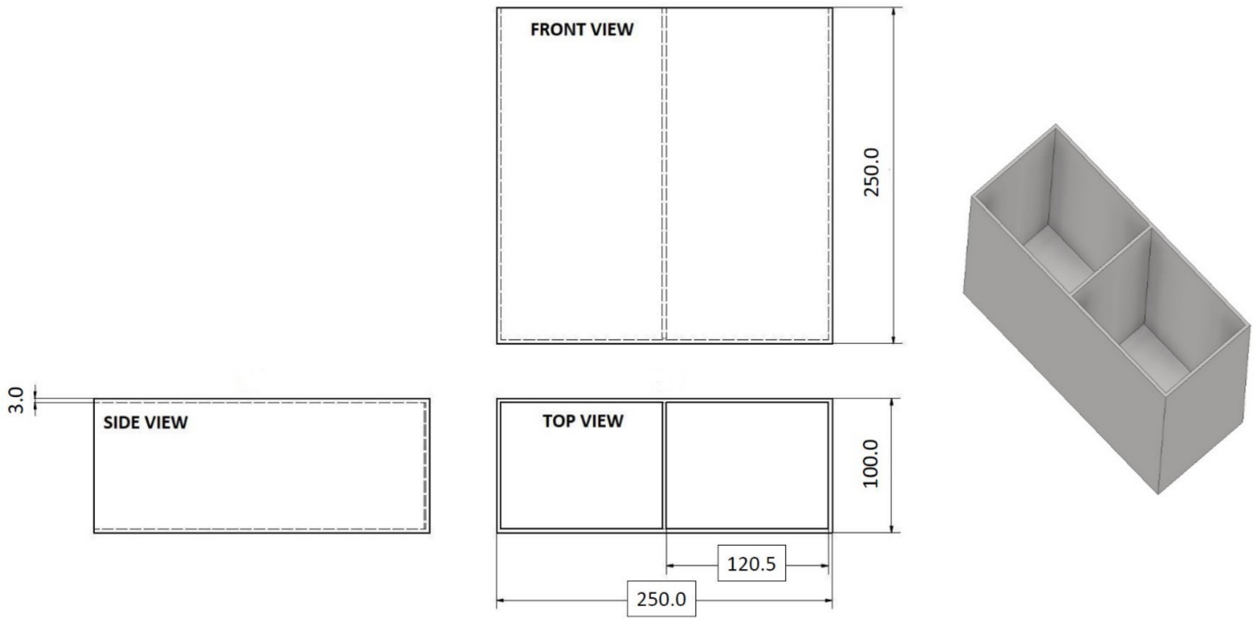

**Figure 1.** Methodology flowchart.

After verifying the thermal and structural criticalities of the molded block, the second operational phase was implemented, i.e., the *analysis phase*. In this phase, the block was analyzed via theoretical and experimental approaches (by means of IRT technique and HFM method). It should be emphasized that the experimental phase was conducted through a Hot Box specifically made for the purposes of this work, described below.

Finally, in the third phase, called *materials recycling phase*, the selected waste materials (polystyrene and wool) were used to fill the air cavities of the block, thus experimentally evaluating their effects on thermal performance.

### 2.2. Design Phase

The design phase of the block was carried out starting from the potential of the 3D printer, whose printing dimensions are 300 × 300 × 400 mm. Therefore, based on these dimensional limits, a block with dimensions of 250 × 250 × 100 mm (width × height × depth) was designed (Figure 2a). Using AutoCAD Inventor®, three-dimensional modeling software, the block was then modeled (Figure 2b).




(**a**) (**b**)

**Figure 2.** Block design (**a**) 2D and (**b**) 3D. (Measurements in millimeters).

Then, once the block prototype was made, all the characteristics required for 3DP were defined using Creality Slicer 4.2 software. At this stage, some very relevant parameters of fabrication were considered, including: the amount of material used, the time required for printing, the structural morphology of the layers needed to ensure mechanical strength, the printing speed, and the type of material used for printing. In this work, the fabrication of the 3D block was performed using PLA: diameter of 1.75 mm, print temperature between 200 and 230 °C, and heat bed temperature between 50 and 60 °C. Figure 3 shows the block design and the definition of the printing characteristics.

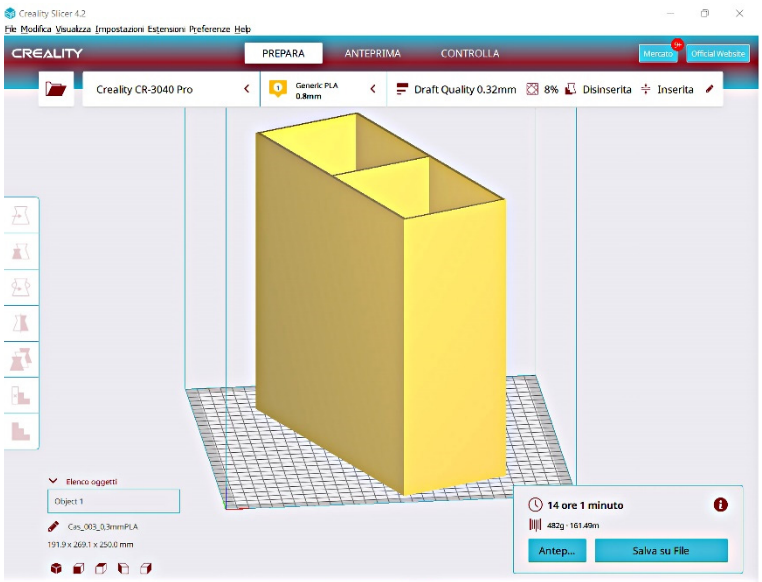



**Figure 3.** Detail of printing characteristics defined using Creality Slicer 4.2 software.

The 3D block production with the characteristics indicated in the slicing software took 14 h and 1 min and 482 g of material. The printing time required is not at all negligible and represents an interesting point for future developments in this area, for example by varying the nozzle diameter and evaluating different printing speeds. Figure 4 shows the final printing phase of the block.

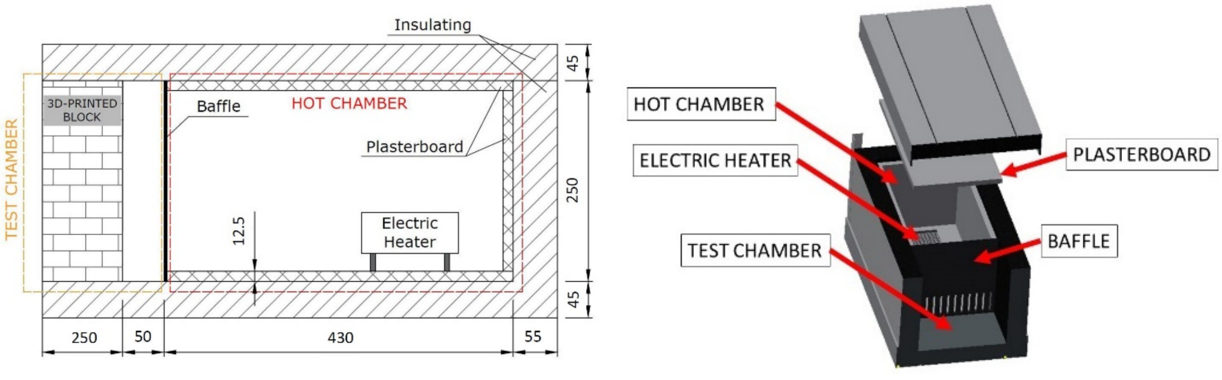

**Figure 4.** Final stages of block fabrication.

*2.3. The Hot Box Apparatus*

To evaluate the thermal performance of the 3D-printed block, a Hot Box capable of providing stationary, controlled, and repeatable operating conditions was designed and built. The design of the Hot Box stems from the experience gained with the Guarded Hot Box of the "Applied Physics Laboratory" of the University of L'Aquila [15,16].

The Hot Box used in this work is composed of a hot chamber, inside which an electric heater has been placed to bring the temperature up to values needed to ensure sufficient temperature differences between the two surfaces of the 3D block. Generally, a temperature difference equal to 20 °C is imposed. The walls of the Hot Box were realized with insulating material, covered with sheet steel. A baffle was inserted near the inner face of the 3D block, to separate the area where thermal energy is introduced (hot chamber) from the area where measurements are carried out (test chamber) and to make any evaluations on radiative heat exchanges.

The dimensions of the Hot Box are 640 × 340 × 360 mm (length × height × width), as shown in Figure 5.




(**a**) (**b**)

**Figure 5.** (**a**) 2D and (**b**) 3D design of the Hot Box. (Measurements in millimeters).

Therefore, based on the design, the Hot Box shown in Figure 6 was created.

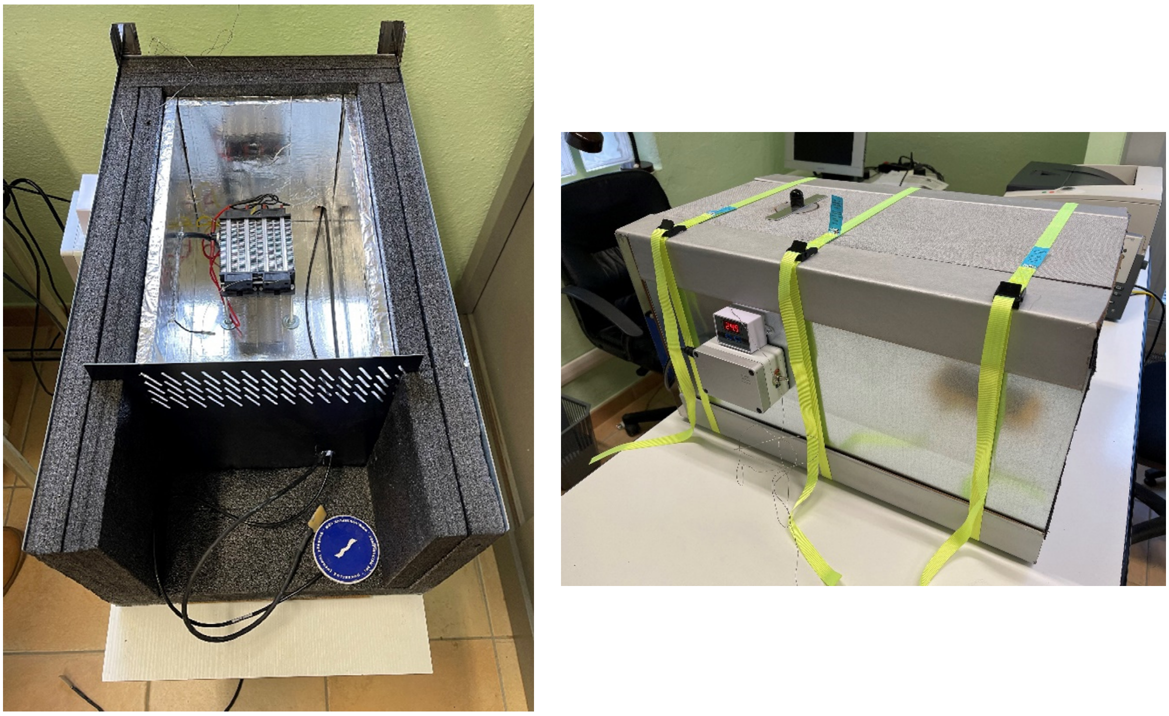


**Figure 6.** The Hot Box setup details.

## 2.4. Performance Analysis

As described in the methodology section, the performance analysis of the 3D-printed block was carried out via theoretical and experimental approaches.

### 2.4.1. Theoretical Approach

The theoretical approach was conducted in first approximation by simplified analysis, using the analogy based on the equivalent electric circuit (the Ohm's law), under steady and one-dimensional conditions. Therefore, considering the temperature differences ($\Delta T$) and electrical resistances ($R$), the heat flux ($q$) through the 3D block can be determined.

Based on the analogous electrical circuit shown in Figure 7, the total electrical resistance $(R_{tot})$ can be derived using Equation (1).

$$R_{tot} = R_{s,i} + R_{cond,1} + R_a + R_{cond,2} + R_{s,e} \quad \left[\mathrm{m}^2 \cdot \mathrm{K/W}\right] \tag{1}$$

where $R_{s,i}$ and $R_{s,e}$ are the internal and external surface resistances [$\mathrm{m}^2 \cdot \mathrm{K/W}$] given by convective and radiative contribution, $R_{cond,\,1}$ and $R_{cond,\,2}$ are the conductive thermal resistances of each PLA layer [$\mathrm{m}^2 \cdot \mathrm{K/W}$], and $R_a$ is the thermal resistance of air layer [$\mathrm{m}^2 \cdot \mathrm{K/W}$]. Surface resistances, $R_{s,i}$ and $R_{s,e}$, were assumed to be, respectively, equal to 0.13 and 0.04 $\mathrm{m}^2 \cdot \mathrm{K/W}$, as indicated by the standard EN ISO 6946 [17], for horizontal direction of the heat flow. The resistance of air layer $R_a$ was assumed to be equal to 0.18 $\mathrm{m}^2 \cdot \mathrm{K/W}$, following the EN ISO 6946 for unventilated air layer. For the conductive resistance of each of the two PLA layers, a value of 0.012 $\mathrm{m}^2 \cdot \mathrm{K/W}$ was considered, obtained considering a thickness of 3 mm and a thermal conductivity $\lambda$ equal to 0.28 W/m·K. Therefore, based on the analogous electrical circuit in Figure 7, the total thermal resistance resulted equal to 0.374 $\mathrm{m}^2 \cdot \mathrm{K/W}$.

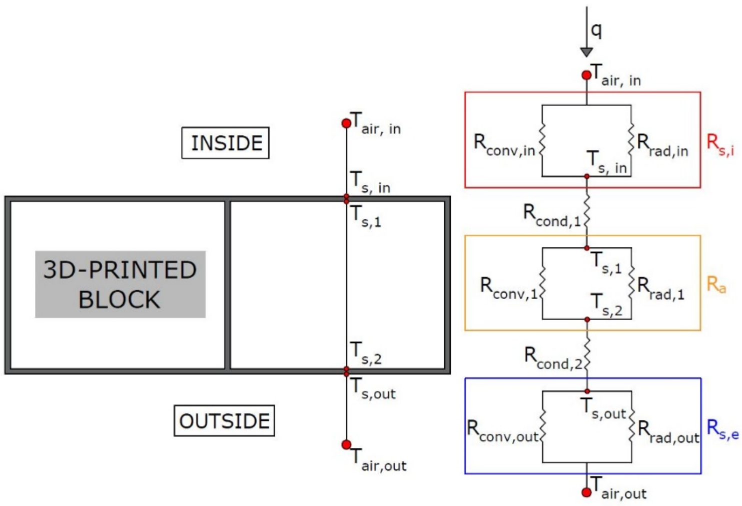



**Figure 7.** Electrical analogy to steady and one-dimensional heat flow of the 3D-printed block, where: R = resistance, T = temperature, q = heat flow.

Given the total thermal resistance, the thermal transmittance $(U)$ of the block, determined using Equation (2), resulted as equal to 2.67 W/m$^2$·K.

$$U = \frac{1}{R_{tot}} \quad \left[\mathrm{W/m^2{\cdot}K}\right] \tag{2}$$

Finally, imposing a temperature difference between the inner and outer surfaces of the block equal to 20 °C, a heat flux through the 3D-printed block equal to 53.4 W/m$^2$ was obtained by means of Equation (3).

$$q = U{\cdot}\Delta T \quad \left[\mathrm{W/m^2}\right] \tag{3}$$

2.4.2. Experimental Approach

The experimental analysis was performed using the Hot Box, described above, which was equipped with temperature and heat flux probes. A schematic representation of the experimental setup employed for the HFM method is shown in Figure 8.

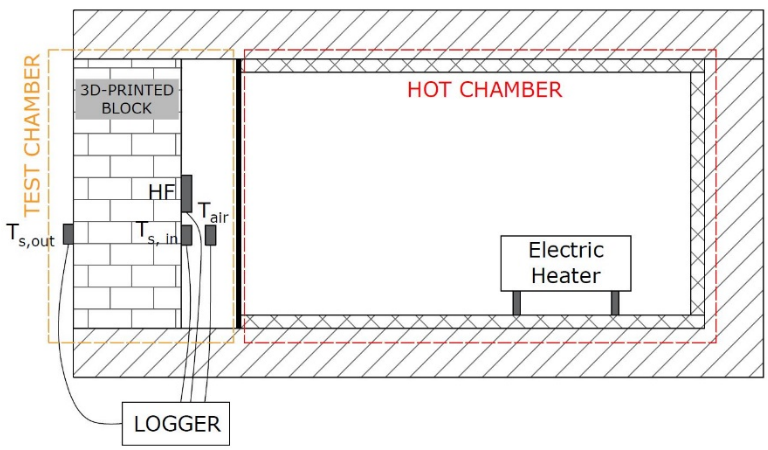



**Figure 8.** Experimental setup for HFM method.

Moreover, to obtain a more in-depth understanding of the thermal behavior of the 3D-printed block, InfraRed Thermography (IRT) technique was performed using a FLIR ThermaCAM® S65 IR camera and the setup shown in Figure 9.

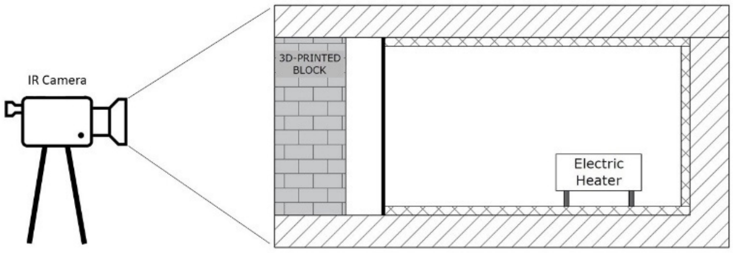



**Figure 9.** Experimental setup for IR thermography technique.

The technical specifications of the measuring instruments are summarized in Table 1.

**Table 1.** Technical specifications of the measuring instruments.

| Sensor | Type | Measuring Range | Resolution |
|---|---|---|---|
| Heat flow meter | Hukseflux HFP01 | From −2000 to 2000 W/m$^2$ | $60 \times 10^{-6}$ V/(W/m$^2$) |
| Surface temperature | LSI Lastem EST124-Pt100 | From −50 to 70 °C | 0.01 °C |
| Datalogger | LSI Lastem M-Log ELO008 | From −300 to +1200 mV | 40 µV |
| IR camera | FLIR ThermaCAM® S65 | 320 × 240 pixels | 0.01 °C |

### 2.5. Use of Recycling Materials

Due to the morphology of the 3D block and implementing the concept of circular economy, waste materials were selected to fill the air cavities of the block. Specifically, two different materials were identified: (1) polystyrene (Figure 10a) and wool (Figure 10b).

(**a**) (**b**)

**Figure 10.** Waste materials used to fill the air cavities of the 3D block. (**a**) Polystyrene. (**b**) Wool.

To know the amount of material inserted into the block cavities, three weighing were performed for (i) empty block, (ii) block with polystyrene, and (iii) block with wool, amounting to 411, 432, and 716 g, respectively, i.e., block densities of 65.8, 69.1, and 114.6 kg/m$^3$.

## 3. Results

Based on the experimental setups, the main results obtained are analyzed below.

### 3.1. Infrared Thermography

The IR thermography technique was performed after achieving stable and steady thermal conditions between the two surfaces of the 3D-printed block. A temperature difference of about 20 °C was obtained with about 45 °C in the hot side and 25 °C in the cold side (i.e., laboratory). The IR thermography helped to understand the thermal stratification in the different configurations: (i) block with air cavities; (ii) air cavities filled with polystyrene; and iii) air cavities filled with wool.

Analyzing the results shown in Figure 11, it is interesting to observe a significant thermal stratification for the block with air cavities, which tends to decrease when the air cavities are filled with polystyrene. When the air cavities are filled with wool, a better thermal behavior is observed with respect to other cases. In fact, thermal homogeneity along the whole 3D block and between block and Hot Box walls is obtained (Figure 11c).

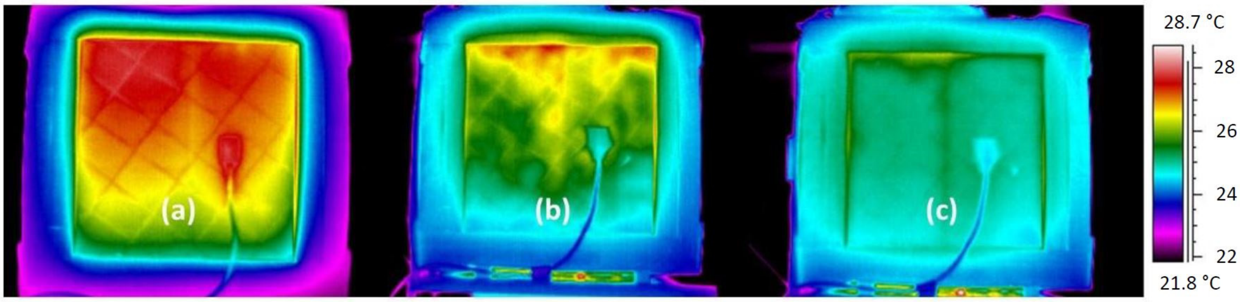



**Figure 11.** IR thermography comparison. (**a**) 3D block with air cavities. (**b**) 3D block with polystyrene. (**c**) 3D block with wool.

### 3.2. Heat Flow Meter Method

The experimental heat flux analysis, conducted using the HFM method, included three tests, and the measured data were analyzed following the "Average Method" proposed by the standard ISO 9869 [18], which allowed one to determine thermal resistance and conductance with Equations (4) and (5), respectively.

$$R = \frac{\sum_{j=1}^{n}\left(T_{s,in,j} - T_{s,out,j}\right)}{\sum_{j=1}^{n} q_j} \qquad \left[m^2{\cdot}K/W\right] \tag{4}$$

$$\Lambda = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n}\left(T_{s,in,j} - T_{s,out,j}\right)} \qquad \left[\mathrm{W/m^2{\cdot}K}\right] \tag{5}$$

where $\sum_{j=1}^{n}\left(T_{s,in,j} - T_{s,out,j}\right)$ is the mean surface temperature difference between inside and outside, and $\sum_{j=1}^{n} q_j$ is the mean density of heat flow.

Each test lasted about 10 h with logging time step of 10 min. The first test was conducted on the 3D-printed block with air cavities, the second on the 3D block and the air cavities filled with polystyrene, while for the third test the cavities were filled with wool. Due to the experimental setup previously described in Figure 8, the values summarized in Table 2 were obtained.

**Table 2.** Main HFM method results.

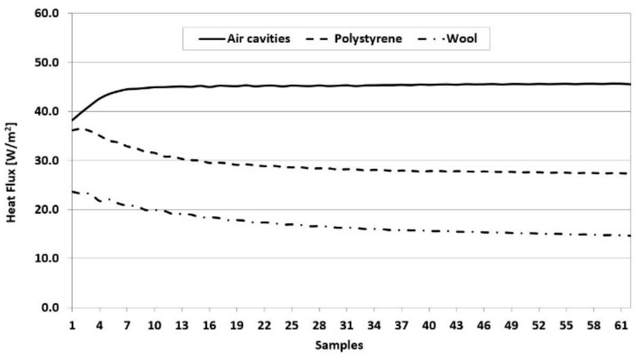
| Case | Mean Heat Flux [W/m$^2$] | Conductance [W/m$^2$·K] | Transmittance [1] [W/m$^2$·K] |
|---|---|---|---|
| 3D block with air cavities | 44.91 ± 3.00% | 3.50 ± 3.15% | 2.19 ± 3.15% |
| 3D block with polystyrene | 29.20 ± 3.00% | 1.57 ± 3.02% | 1.24 ± 3.02% |
| 3D block with wool | 17.11 ± 3.00% | 0.78 ± 3.05% | 0.69 ± 3.05% |

[1] Obtained considering internal and external surface resistances respectively equal to 0.13, 0.04 m$^2$·K/W [17].

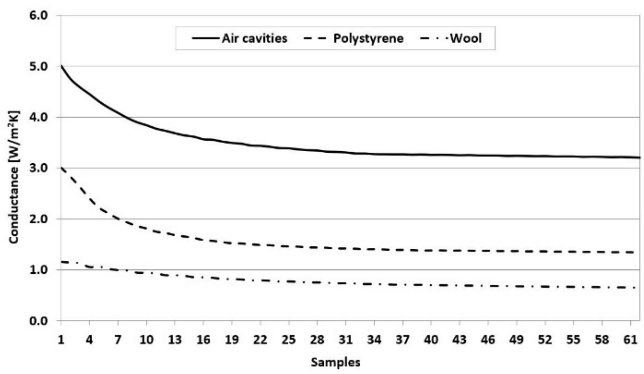
It is worth noting to analyze the difference between theoretical and experimental values obtained for the 3D block with air cavities. In terms of thermal transmittance, the theoretical approach provided a value of 2.67 W/m$^2$·K, i.e., 21.7% higher than the experimental data (equal to 2.19 W/m$^2$·K); in terms of heat flux, the theoretical analysis determined a value of 53.4 W/m$^2$, i.e., 18.9% higher than the heat flux obtained experimentally (equal to 44.9 W/m$^2$). The difference between theoretical and experimental values are probably due to three causes: (i) the use of a simplified theoretical approach, i.e., based on a one-dimensional and stationary approach; (ii) the employment of air thermal resistance ($R_a$) taken from the standard EN ISO 6946 [17] and, therefore, intrinsically approximate; and (iii) measure error by the HFM which is inherently characterized by its accuracy.

**Remark 1.** *The uncertainty analysis was carried out following the Holman's method [19].*

The graphical analysis of the results obtained is shown in Figure 12. The results highlight that the thermal performance of the 3D-printed block improves when the air cavities are filled with polystyrene and wool and that the wool showed the best thermal behavior, with a thermal transmittance value of 0.69 ± 3.05% W/m$^2$·K.




(**a**)




(**b**)

**Figure 12.** Results comparison. (**a**) Heat flux. (**b**) Conductance.

## 4. Conclusions

In this work, a 3D-printed block is presented in order to evaluate potential opportunities to exploit additive manufacturing for improving the energy performance of the buildings' opaque envelope.

The 2D and 3D design allowed the block fabrication, and therefore, the performance analysis was carried out theoretically and experimentally, through IR thermography technique and HFM method. In particular, the experimental analysis was carried out thanks to the use of a specially made Hot Box.

In addition, following the circular economy concept, the air cavities of the block were filled with waste materials such as polystyrene and wool.

The main findings of the work highlighted that:

- The 2D and 3D design phase of the block using different software (including AutoCAD Inventor® and Creality Slicer 4.2 software) allowed one to exploit the potential of the AM to create even complex geometries; however, the printing phase may require a non-negligible time that, therefore, must be evaluated in the design phase. In this work, the printing phase required about 14 h to realize the prototype block; therefore, an interesting future development of the work is represented by the research of solutions able to reduce the printing time, for example, modifying the diameter of the nozzle and evaluating different printing speeds; the use of AM allowed one to study solutions for reusing waste materials to be filled in the air cavities of the block, thus implementing the concept of circular economy;
- The IR thermography has shown that the 3D-printed block with the air cavities is subject to a considerable thermal stratification that tends to decrease when the cavities are filled with polystyrene and wool;

- The HFM method allowed one to have a quantitative knowledge of the thermal behavior of the 3D-printed block in the three configurations analyzed (with and without cavity filling materials);
- Filling the air cavities with wool determined the best thermal behavior with a thermal conductance value of 0.78 $W/m^2 \cdot K \pm 3.05\%$, with respect to polystyrene with which a conductance equal to 1.57 $W/m^2 \cdot K \pm 3.02\%$ was obtained. Clearly, the results obtained are still far from the thermal performance of high-insulating materials, already used in the construction sector. However, this work represents a first step toward the use of additive manufacturing in the field of building insulating materials, and given the potential of AM, significant improvements can be expected.

In conclusion, this work represents a first approach to using an emerging technology, such as AM, to create a prototype 3D-printed block as a building's thermal insulation. Future developments of this work will allow for the development of additional 3D-printed block geometries, also including different printing materials and waste materials for air cavity filling.

**Funding:** This research was funded by "Progetti di Ateneo per Avvio alla Ricerca, Decreto del Rettore n. 786 del 13.07.2021".

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not Applicable.

**Acknowledgments:** This work was realized with the fundamental technical support of Giovanni Pasqualoni.

**Conflicts of Interest:** The author declares no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

## References

1. International Energy Agency (IEA). Data and Statistics. Available online: https://www.iea.org/data-and-statistics/data-browser?country=WORLD&fuel=Energy%20consumption&indicator=TFCShareBySector (accessed on 6 December 2021).
2. International Energy Agency (IEA). *CO2 Emissions from Fuel Combustion*; Beyond 2020 Online Database; International Energy Agency: Paris, France, 2012.
3. International Energy Agency (IEA). *World Energy Outlook*; International Energy Agency: Paris, France, 2021.
4. de Rubeis, T.; Falasca, S.; Curci, G.; Paoletti, D.; Ambrosini, D. Sensitivity of heating performance of an energy self-sufficient building to climate zone, climate change and HVAC system solutions. *Sustain. Cities Soc.* **2020**, *61*, 102300. [CrossRef]
5. Pajonk, A.; Prieto, A.; Blum, U.; Knaack, U. Multi-material additive manufacturing in architecture and construction: A review. *J. Build. Eng.* **2022**, *45*, 103603. [CrossRef]
6. Wangler, T.; Roussel, N.; Bos, F.P.; Salet, T.A.M.; Flatt, R.J. Digital concrete: A review. *Cem. Concr. Res.* **2019**, *123*, 105780. [CrossRef]
7. Pessoa, S.; Guimarães, A.S.; Lucas, S.S.; Simões, N. 3D printing in the construction industry—A systematic review of the thermal performance in buildings. *Renew. Sust. Energ. Rev.* **2021**, *141*, 110794. [CrossRef]
8. He, Y.; Zhang, Y.; Zhang, C.; Zhou, H. Energy-saving potential of 3D printed concrete building with integrated living wall. *Energ. Build.* **2020**, *222*, 110110. [CrossRef]
9. Grabowska, B.; Kasperski, J. The Thermal Conductivity of 3D Printed Plastic Insulation Materials—The Effect of Optimizing the Regular Structure of Closures. *Materials* **2020**, *13*, 4400. [CrossRef] [PubMed]
10. Mihalache, A.; Hrituc, A.; Boca, M.; Oroian, B.; Candrea, I.; Botezatu, C.; Slatineanu, L. Thermal Insulation Capacity of a 3D Printed Material. *Macromol. Symp.* **2021**, *396*, 2000286. [CrossRef]
11. Sarakinioti, M.V.; Turrin, M.; Konstantinou, T.; Tenpierik, M.; Knaack, U. Developing an integrated 3D-printed façade with complex geometries for active temperature control. *Mater. Today Commun.* **2018**, *15*, 275–279. [CrossRef]
12. Maier, M.; Salazar, B.; Unluer, C.; Taylor, H.K.; Ostertag, C.P. Thermal and mechanical performance of a novel 3D printed macro-encapsulation method for phase change materials. *J. Build. Eng.* **2021**, *43*, 103124. [CrossRef]
13. Hager, I.; Golonka, A.; Putanowicz, R. 3D printing of buildings and building components as the future of sustainable construction? *Procedia Eng.* **2016**, *151*, 292–299. [CrossRef]
14. News Europena Parliamnet. Available online: https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits (accessed on 15 December 2021).
15. de Rubeis, T.; Muttillo, M.; Nardi, I.; Pantoli, L.; Stornelli, V.; Ambrosini, D. Integrated Measuring and Control System for Thermal Analysis of Buildings Components in Hot Box Experiments. *Energies* **2019**, *12*, 2053. [CrossRef]

16. de Rubeis, T.; Nardi, I.; Muttillo, M. Development of a low-cost temperature data monitoring. An upgrade for hot box apparatus. *J. Phys. Conf. Ser.* **2017**, *923*, 012039. [CrossRef]
17. *EN ISO 6946:2017*; Building Components and Building Elements—Thermal Resistance and Thermal Transmittance—Calculation Methods. European Committee for Standardization: Brussels, Belgium, 2017.
18. *EN ISO 9869-1:2014*; Thermal Insulation—Building Elements—In-Situ Measurement of Thermal Resistance and Thermal Transmittance, Part 1: Heat Flow Meter Method. European Committee for Standardization: Brussels, Belgium, 2014.
19. Holman, J.P. *Experimental Methods for Engineers*, 8th ed.; McGraw-Hill Series in Mechanical Engineering: New York, NY, USA, 2012; ISBN 13: 9780073529301.