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Conceptual design for an additively manufactured building brick

Paulo González, Engineering BSc[1], Liz Pimentel, Engineering BSc[1], Antonio Alberto Jaén Ortega Engineering MSc[1], and Maria De Los Ángeles Ortega Del Rosario, PhD[1,2*]
[1]Universidad Tecnológica de Panamá, Panamá, paulo.gonzalez@utp.ac.pa, liz.pimentel@utp.ac.pa, antonio.jaen@utp.ac.pa, maria.ortega@utp.ac.pa
[2]Sistema Nacional de Investigación (SNI), Clayton Ciudad de Panamá, Panamá
*Corresponding author: maria.ortega@utp.ac.pa

Abstract– ***Additive manufacturing (AM) is an attractive fabrication method in several industrial fields, including the construction sector, also called Architecture, engineering, and construction industry (AEC). This technique's popularity is continuously growing due to the benefits over traditional methods, such as rapid production, custom parts, and reduced material waste, offering opportunities to develop complex shapes with geometric freedom and a high degree of detail and achieving a high degree of automation. Addressing AM from the early stages of conceptual design allows greater exploitation of its benefits. Thus, this study tackles a conceptual redesign approach to adapt traditional bricks into additively manufactured bricks. The methodology was inspired by conceptual design as defined by VDI 2221, including design thinking mindsets as a source of idea generation. A functional analysis was performed to characterize this product and obtain two redesign options: internal diamond-shaped and rectangular-shaped cells, with the possibility of integrating phase change materials. A numerical analysis showed that the rectangular-shaped cells using AM-adapted concrete complied with ASTM C90 standardized bricks.***

Keywords—Additive manufacturing, VDI 2221, brick, concrete, 3D concrete printing

I. INTRODUCTION

The use of digital tools to deal with problems and challenges in several commercial and industrial sectors, including the construction sector, has become common in the last decade [1], [2] since they provide opportunities to obtain well-tailored parts and structures capable of being adapted to specific functions [3]. In several other sectors, such as automotive, aerospace, food industry and processing, aeronautics, and medical field, among many others, digital transformation, typical of industry 4.0, has been a great ally [4]–[8], which has also served as a pathway to achieve sustainability [9]–[11] and to face the many challenges that COVID-19 pandemic has left worldwide [12], [13].

Among the manufacturing techniques well adapted to digital transformation is additive manufacturing (AM). Additive manufacturing is defined according to ISO/ASTM 52900, 2021 as the "process of joining materials to make objects from 3D model data, usually layer upon layer" [14]. It consists of manufacturing parts in 3D, usually characterized by complex geometries, adding layer upon layer of material to make it solid, generally using computer-aided designs (CAD) models. This technique's popularity is continuously growing due to the benefits over traditional methods, such as rapid production, custom parts, and reduced material waste, among many others. In addition, it has applications in the aerospace, automotive, medical, architectural, artistic, gastronomic, and construction fields.

Among the several advantages that AM offers, one can mention that complex shapes can be generated, with geometric freedom and a high degree of detail, in addition to achieving a high degree of automation, reducing the need for human intervention in processes, costs, investment times and associated risks [15]. Therefore, AM has the potential to reduce the waste of materials, reduce the labor time of the workers associated with the project and reduce the time associated with the manufacturing process, improving sustainability in construction [3], [16]–[22].

Thus, AM can find a potential development in the construction sector, also referred as Architecture, engineering and construction industry (AEC), which is one of the largest industries worldwide, one typically characterized by traditional and, in some cases, somewhat manual activities due to several complexities and multidisciplinarity and uniqueness of its products, showing a lower degree of digitalization [23]–[26] and most labor accident prone.

Addressing AM from the early stages of conceptual design allows greater exploitation of its benefits since functions and restrictions such as lightness, sustainability, and use of material, among others, can be defined as objective functions of the design, impacting the geometries and architectures of the product [27]. Geometry has been a key point in using AM since it has a virtually infinite capacity for generating shapes, and different sources of inspiration have been analyzed to obtain the geometry. In some cases, this is based on traditional geometries, seeking to adapt naturally to the existing market [28]–[30]. The most recent studies explore the modifications of both the internal and external geometries of bricks [31], [31]–[33] for non-structural parts and geometries curves in large-scale structures, such as walls and others [34]–[36].

Few studies are addressing the redesign opportunities for traditional bricks by applying this kind of technology. Thus, this study tackles a conceptual redesign approach to adapt traditional bricks into additively manufactured bricks. Here, the methodology is inspired by product design guidelines of VDI 2221, specifically addressing functional analysis, coupled with the user perspective taking and empathy as defined by the Design Thinking approach.

Functional analysis is a common approach used in industry to achieve innovation and can be very well adapted to redesign current products [37], and within VDI 2221, it has been previously used as a design and redesign methodology [38]–[40]

Therefore, this study focused on the following research question: Which redesign opportunities may be considered to develop an additively manufactured building brick based on guidelines approached by a conceptual design and inspired by a potential user perspective?

II. METHODOLOGY

A. *Methodology description*

This study aimed to perform a conceptual design of a building brick suitable for decorative walls fabricated by additive manufacturing. Here, a redesign methodology is proposed inspired by product design guidelines of VDI 2221 coupled with the user perspective taking and empathy as defined by the Design Thinking approach.

B. *Task clarification and requirements*

The methodology for this product redesign started stating the task clarification resulting in the definition of the product requirements. In this case, this redesign sought to define a geometry capable of complying with all the technical requirements of a traditional building brick but adapted to additive manufacturing techniques while developing a sustainable process. The technical factors included mechanical resistance, based on national and international standards for traditional building bricks such as DGNTI- COPANIT 48-2001 [41], which regulates the manufacturing technique of structural and non-structural hollow concrete bricks in Panama, and the ASTM C90 [42] establishes the specifications for hollow concrete bricks for structural and non-structural use, such as dimensional tolerances, minimum layer and thicknesses for hollow units, minimum strength and maximum absorption requirements, and maximum linear shrinkage.

The initial requirements were limited to include additive manufacturing as the fabrication technique and achieving sustainability by including eco-design principles either as functions or restrictions during the product life cycle stages as defined by the ISO/IEC standards 15288 [43], [44]. A technical questionnaire was conducted among the Mechanical Engineering Department at the Universidad Tecnológica de Panamá due to the similarities in the educational background and the relevance to the field of study of the respondents.

This questionnaire aimed to know the behavior of potential users in the construction market and their decision-making, compared to design parameters, to observe the prioritization of brick characteristics. Besides, as consumers, their perspective could strengthen both the requirements definition and the product functions during its different life cycle stages while performing the functional analysis.

Information containing the purpose of this study and confidentiality was disclosed. These questions were designed to recognize the potential users' perspective. Thus, the questionnaire consisted of fourteen questions related to technical, aesthetic, and economic factors concerning building bricks. Participation of 374 of a population of 2844 was obtained. A confidence level was calculated using OpenEpi, resulting in a sample that exceeded 95% reliability (see Table I).

TABLE I
SAMPLE SIZE FOR FREQUENCY IN A POPULATION (FROM OPENEPI, VERSION 3, OPEN-SOURCE CALCULATOR —SSPROPOR).

Population size (for finite population correction factor or fpc) (*N*)	2844
Hypothesized % frequency of outcome factor in the population (*p*)	50%+/-5
Confidence limits as % of 100(absolute +/- %) (d):	5%
Design effect (for cluster surveys-DEFF):	1
Confidence level (%)	
95%	339
The equation for sample size	n = [EDFF·Np(1-p)]/ [(d^2/z_(1-α/2)^2·(N-1)+p·(1-p)]

C. *Functional Analysis*

Once the initial requirements were defined, a functional analysis was performed. Here, a hierarchization based on a functional tree was performed, defining principal functions, service functions, and restrictions. The first type included the basic functions the product must perform during its life cycle to achieve its tasks, according to the characteristics or design, but also considering the existing regulations. The service functions are considered a lower hierarchy of functions that provide service or generate the conditions to achieve the main functions. Restrictions include all limits and conditions that must be avoided during the product life cycle. In this section, any critical interaction between the surrounding elements (users, primary, secondary, and other factors) and the product were analyzed and recorded functionally without including existing or new design solutions. To do this, a brainstorming process suggested on a methodology proposed by [45] was performed considering two perspectives: potential residence occupants, and designers, engineers and architects of the construction sector. These interactions were defined between users, external factors to the product, and other factors.

Product functions must be hierarchized during the design process, accounting for factors that are more relevant to the design and fabrication of additively manufactured building bricks. After this, these functions were characterized, meaning that quantifiable criteria were defined, allowing designers to implement said characteristics in models and drawings and the engineers to validate that the requirements have been adequately considered since it also references documents. In this section, the prioritization of the functions is also carried out. For this, flexibility levels can be assigned to each criterion: F0 could indicate that the criterion is a necessity in the design, F1 means that the criterion has flexibility when it comes to implementation, and F2 could indicate that the criterion is agreeable but not a necessity [45]. Finally, the conceptual design is achieved here, finding potential solutions for the possible new geometries due to the redesign process.

D. Redesign and numerical simulations

Computational-aided design (CAD) was performed using AutoDesk Fusion 360® since it offered a user-friendly environment to draw and export these bricks. Due to its ease of declaring materials, ANSYS Mechanical® Software was the selected tool to carry out the compression tests. The material that was chosen for the simulations was AM-adapted concrete because it is the most used material in the construction sector and allowed us to compare the results with the standards and the literature. These materials were previously tested experimentally by [46], defining Young's modulus as a time function (see Table II).

TABLE II
MECHANICAL PROPERTIES OF AM ADAPTED CONCRETES, WHERE YOUNG'S MODULUS IS A FUNCTION OF TIME, WHERE "T" IS THE TIME IN MINUTES. EXTRACTED FROM [46].

Parameter	Value
Vertico & Sika concretes	
Mass (kg/m^3)	2500
Young's modulus (N/mm^2)	0.0032t+0.048
Poisson's ratio	0.22
Webber 115, Webber 145/2	
Mass (kg/m^3)	2000
Young's modulus (N/mm^2)	0.0012t+0.078
Poisson´s ratio	0.25

To know the properties of the concrete, the Voxelprint® extension of Rhinoceros® and Grasshopper® software was used, which allows the brick to be visualized in "voxels," which are a unit of graphic information that defines a point in three-dimensional space and could further simulate the layered structure of additively fabricated bricks.

III. RESULTS AND ANALYSIS

A. Questionnaire Results

From this questionnaire, technical and non-technical factors were analyzed among the respondents. Five technical parameters were surveyed, and mechanical resistance (25,9%) was considered the most influential for this product among the survey respondents. Indoor temperature (21%), outside noise reduction (19,3%), solar light control (17,3%), and energy savings (16,5%) were also considered (Figure 1, left). Besides the technical performance of the building brick, four parameters were mainly considered among the questions: quality/cost ratio, aesthetics, sustainability, and the inclusion of additional insulating materials such as phase change materials (PCM) (Figure 1, middle), in which the former is considered as the most relevant, and the latter one, as the least relevant when deciding to buy this product (Figure 1, right).

These results revealed for this study that the quality/cost ratio is even more relevant than the mechanical resistance for respondents. However, complying with at least the minimum established in standards is an initial requirement; thus, during the characterization, all these factors must be considered as F0. Furthermore, this revealed a need to maintain competitive costs in these products, which may be challenging considering that an innovative fabrication process through AM is required.

Furthermore, based on the questionnaire, the respondents were encouraged to comment on various design factors or parameters that should be considered within the functional analysis of the building brick. A text frequency analysis was performed to identify these comments' main factors and clusters. Four clusters were identified from this analysis. The most frequent comments were related to the mechanical performance of the building bricks accounting parameters such as mechanical resistance, life span, behavior during natural disasters, and impermeability. Comments related to the cost of the building brick and the geometry and process, including shape and sustainability, were also frequent among the answers. A fourth cluster related to aesthetic factors was also observed.

These four clusters may be analyzed as follows:

1. The most relevant factor among the answers is related to the building brick's mechanical performance. Most of the comments expressed the need for the brick to withstand external forces such as vibrations and weather-related (natural disasters). Additionally, it was mentioned in several answers that the life span of the brick must be adequate to be feasible for the expected applications.
2. The second cluster of factors was related to the geometry and the manufacturing process parameters, as several comments highlighted the importance of the brick having an optimal shape to be a viable option over conventional bricks. In addition, some respondents considered issues such as the union between bricks and its sustainability to be essential within this factor.
3. The quality-cost ratio of the brick was outstanding within the survey results. However, it was not a much-discussed topic in the comments of those surveyed who highlighted that the material should be of quality, maintaining an affordable price for the population.
4. Finally, there is the aesthetics of the brick, in which they focused on the design of the brick and the possibility that it had colors.

B. Functional Analysis

Functional analysis was performed as an iterative process for both residence occupants and the AEC industry. The first idea generation was based on the theoretical background of building bricks and the initial requirements established during the task clarification. The results can be observed in Figure 2. However, this functional analysis was enhanced by perspective-taking and empathy from potential users, as defined in Design thinking. Thus, a second iteration accounting for the questionnaire analysis was performed, as observed in Figure 3.

The first iteration led to nine principal functions, for the building occupants and eleven, for the AEC industry. Among them, one can find:

F1 → Reduce the energy use of the occupants of the residence.

F2 → The cost of the brick must be accessible for both occupants and AEC companies.

F3 → The brick must accomplish sustainability.

F4 → The brick must have high resistance to withstand external forces.

Once potential users' perspectives are accounted for, some functions were added, increasing their count to twenty-one.

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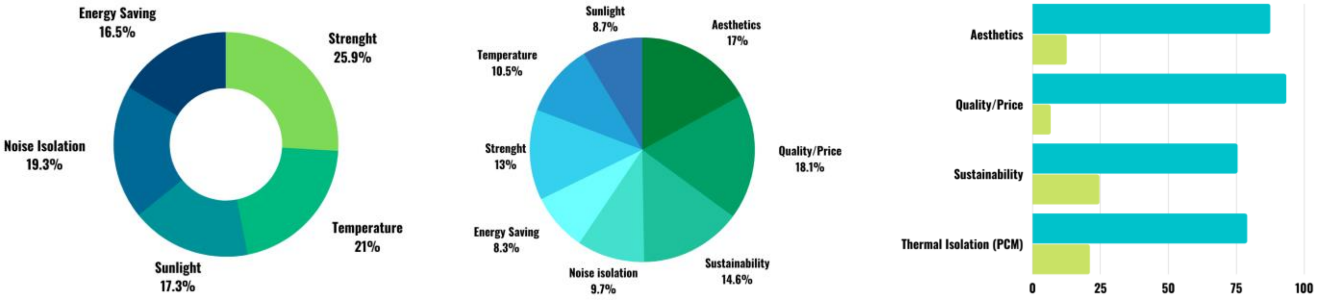


Fig. 1 Design and selection factors considered on this questionnaire for building brick design when considering only technical factors (left) and when considering technical and non-technical factors (right).

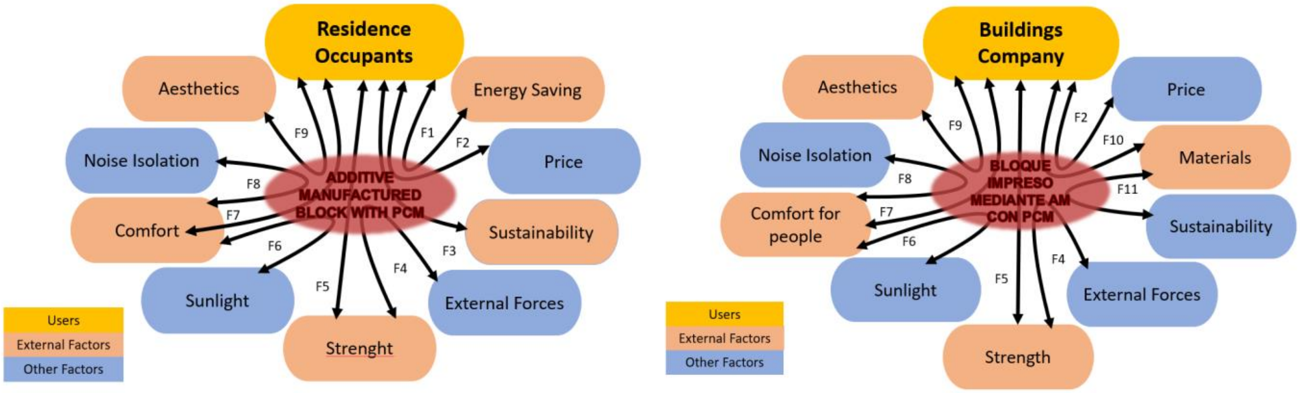


Fig. 2 Idea generation for a building brick based on previous knowledge and guidelines.

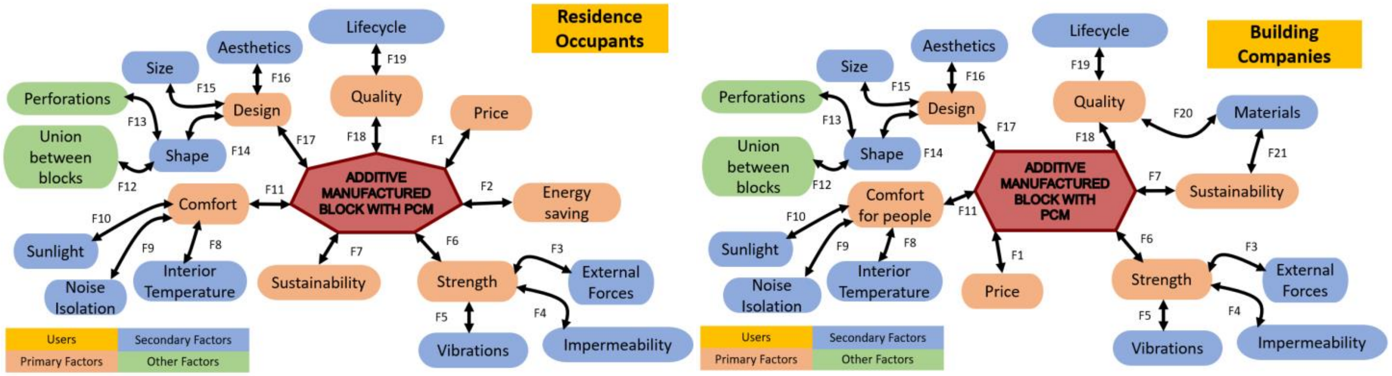


Fig. 3 Idea generation for a building brick based on previous knowledge and guidelines enhanced with perspective-taken and emphathy from potential users..

TABLE II

FUNCTIONAL TREE WITH THE LIFE CYCLE STAGES, SERVICE FUNCTIONS AND RESTRICTIONS.

Principal function	Life cycle stage	Service Function	Restrictions
F1. The cost of the brick must be accessible to both occupants and businesses.	Transport and distribution	F1.1. The cost-quality ratio must be competitive in the market.	FR1. The price should not exceed 10 times the cost of conventional bricks.
F2. Reduce the energy expenditure of the residents.	Use	F2.1. The use of the bricks must represent a decrease in the energy expenditure that is destined for the conditioning of the enclosure.	
F3. The brick must have high strength to withstand external forces.	Design, selection of materials and use.	F3.1. Have a high impact resistance.	FR3. It must not be damaged when subjected to external forces.
F4. It must have a high percentage of impermeability, i.e., resistance to moisture.	Design, material selection, and use	F4.1. Water, mainly rainwater, should penetrate as little as possible into the material.	FR4. Moisture should not reach the interior of the enclosure.
F5. The brick must be vibration resistant.	Design, selection of materials and use.	F5.1. The walls must present a minimum of cracks and/or other wear after mild external excitations (earthquakes).	FR5. The structure should not yield easily to slight vibrations.
F6. The brick must be sturdy for customer use.	Design, selection of materials, and use.	F6.1. They must withstand compression, bending, and tension stresses following the provisions of the regulations. (2)	FR6. It must not be damaged when subjected to external forces.
F7. Materials must be environmentally sustainable.	Manufacture, Use, design, and end of life.	F7.1 Materials must have a low water and carbon footprint. (1) F7.2 Minimize pollution emissions. (1) F7.3 Minimization and elimination of waste. (1) F7.4 Reduce energy consumed and consumption of natural resources. (1) F7.5 Design for lifetime costs. (1) F7.6 Use of recycled products (1)	FR7. The materials used cannot come from unsustainable sources.
F8. The temperature inside should be comfortable for the people in residence.	Design and selection of materials.	F8.1. The phase-change material shall contribute to absorbing some of the excess heat.	FR8. Phase-change material should not leak out of confinement.
F9. Maintain a comfortable sound pressure level.	Design, selection of materials, and use.	F9.1. Materials should be insulating (dense and rigid) like concrete.	
F10. Prevent radiation from entering the enclosure.	Design, selection of materials, and use.	F10.1. The material must reflect most of the solar radiation.	
F11. The brick must maintain a pleasant comfort within the building.	Design, selection of materials, and use.	F11.1. The thermal conductivity of the material should be low. F11.2. The material must have high density since, at the same time, these materials have greater thermal inertia (concrete or cement). F11.3. It will be recommended to place windows in strategic locations to improve natural convection in the enclosure*	FR11. There should be no heat buildup on the walls or in the enclosure.
F12. The shape of the brick should ensure optimal assembly between the bricks.	Design and use	F12.1. Must have a gasket.	
F13. The shape of the brick should allow the possibility of drilling.	Design and use	F13.1 Areas where drilling will be permitted shall be marked.	FR13. Perforations should not affect the compartments where the PCM is contained.
F14. The design of the brick shape should be optimal.	Design	F14.1. Must satisfy structural and safety requirements.	
F15. The size of the brick design must be standardized with conventional ones.	Design	F15.1. Dimensions must comply with DGNTI-COPANIT 48 – 2011 and ASTM standards.	
F16. The brick should be aesthetically pleasing to customers.	Design and use	F16.1 Allow the user to customize the color of the façade according to their taste.	FR16. Use geometries that are efficient, but at the same time pleasing to the customer's eye.
F17. The design of the brick should be eye-catching and efficient for buyers.	Design and use	F17.1. It must meet the needs of customers. F17.2. Must have competitive and innovative design.	FR17. It should not be the same as the traditional brick.
F18. The brick must be of quality for both the occupants and the companies.	Design and selection of materials.	F18.1. Must have strict quality control. F18.2. Must provide security.	
F19. The life of the brick must be long, which guarantees the quality of the product.	Design, selection of materials, and use.	F19.1. Must withstand design loads and fortuitous events.	FR19.1. It must not require the demolition of the structure.
F20. The materials for the manufacture of the brick must be of quality for customers.	Use	F20.1. Materials must ensure durability. F20.2. Good Layer Adhesion F20.3. The method ensures pumpability. F20.4. Good geometry F20.5. Good distribution of the isolation of the PCM.	FR20. Do not choose materials that do not meet the brick's required quality standards.

F21. The cost of materials should be low.	Manufacturing	F21.1. Use resources efficiently.	FR21. There should be no waste of the material.

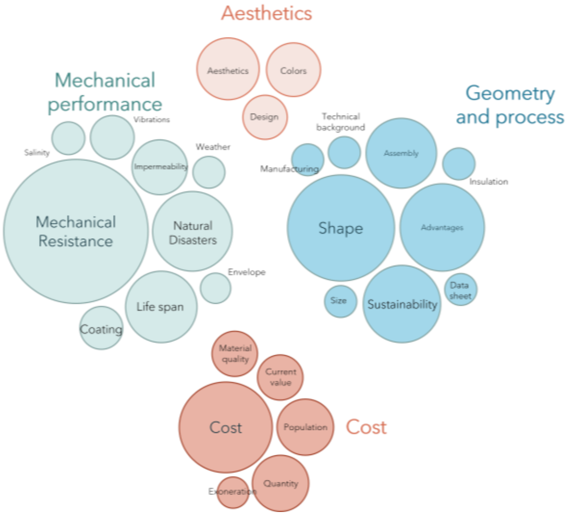


Fig. 2 Packed bubble chart of word frequency of respondents' comments regarding design factors or parameters to consider during the building brick functional analysis.

Some functions regarding vibrations, impermeability, assembly, aesthetics, and life span appeared as the result of this analysis. Besides, the cost was now considered the highest hierarchy of functions since it was the main factor when designing and fabricating building bricks for the respondents. The results from this functional analysis can be observed in the functional tree developed in Table II.

Moreover, based on the questionnaire, the respondents were encouraged to comment on various design factors or parameters that should be considered within the functional analysis of the building brick. Their responses were arranged in four clusters displayed in Figure 4, and these clusters served to further establish a hierarchy among the functional analysis.

Finally, the relevant criteria were characterized according to the initial requirements and the functional analysis. Table III shows the most relevant criteria defined for the building brick.

C. *Brick geometry redesign*

Here, two approaches could be taken: propose a new geometry that could be adapted to the different requirements from the functional analysis or redesign a building brick based on said requirements. Since the cost was one of the main factors among the respondents, and potential users must analyze a new geometry, and their mechanical capabilities must be tested, this study focused on the second approach.

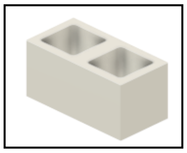
Then, this study used the base geometry developed previously by [47] and the commercial bricks established by Panamanian standards [41]. The study of [47] was chosen since it was additively manufactured and experimentally tested to comply with different ASTM standards and in which the behavior of different configurations of bricks made of stoneware is investigated to find out their mechanical properties and other printing parameters.

Two main results were obtained. The first brick (B1) is a diamond-geometry brick inspired by the study of [47] and adapted to the size and shape of standardized bricks. Here, the main proposal is to add PCM to the internal holes of this brick. This geometry was selected since it offers high resistance to compression, according to the previous results.

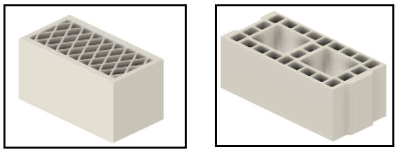
The second result was brick (B2), a redesign from standardized commercial bricks. Here, the internal geometry was modified to add a configuration based on cells, as suggested by [47], but in this case, these internal structures were rectangular, which can be done by a fabrication based on AM. Furthermore, from the functional analysis, adding a female-male interlocked union between bricks may ease the assembly stage during its life cycle, allowing quick repairment if needed and extending the potential lifespan of a wall. PCM can reduce the external solicitations from solar radiation and others, promoting internal thermal comfort for the occupants. Moreover, these structures may be adapted to be structures reinforced by metal bars if necessary for structural bricks. The geometric parameters and shape for each brick are defined in Table III, and Fig 3.

TABLE III
GEOMETRY PROPOSED FOR THE BRICKS.

Parameter	Commercial Brick	B1	B2
Height	194 mm	194 mm	194 mm
Width	397 mm	397 mm	397 mm
Thickness	194 mm	194 mm	194 mm
Volumen	7.483 x10^{6} mm3	7.718 x10^{6} mm^{3}	7.718 x10^{6} mm^{3}
Total surface	38574.726 mm^{2}	39,784.739 mm^{2}	39,784.739 mm^{2}
Density	0.001 g/mm3	0.001 g/mm^{3}	0.001 g/mm^{3}
Internal cell area	19192.507 mm^{2}	583.321 mm^{2}	583.321 mm^{2}
Distance between two cells	32 mm	6.111 mm	6,111 mm



Commercial Brick



Brick – B1
(Redesign from a Commercial Block

Brick – B2
(Redesign from Cruz, 2020)

Fig. 3 Geometry proposed for a commercial brick according to ASTM C90 standard, and Brick B1, and B2.

D. *Numerical tests*

Finally, these bricks were tested by performing a numerical simulation following ASTM C90 [42] and DGNTI-COPANIT-48-2001 [41]. For the simulation, the external load was calculated according to the minimum stresses established in the ASTM C90 standard using the stress formula:

$$P_{C90\ MIN} = \sigma_{C90\ MIN} * A_{total} \tag{1}$$

In which, $\sigma_{C90\ MIN}$, is the minimum compressive load required and, in this case, 11,7 MPa, $P_{C90\ MIN}$, is the applied load, and A_{total}, is the total surface area of the brick.

The commercial brick was used to calculate the load since they comply with standards serving in this study as a reference. The calculated load that was applied in the simulation is 452 kN. In addition, a time of 28 days was taken as the standard age for these tests, following the guidelines and lessons learned from the literature [48], [49]. Since Young's time-dependent modulus equation is in minutes, 28 days accounted for 40320 min.

Finally, eighteen probe points were placed in the different bricks to test their compressive strength. These results can be observed in Table IV. A similar behavior was observed when using Vertico/Sika concrete and Weber concrete (see table IV). Here, as expected, the commercial brick withstands the standardized loads. However, B1 did not comply with withstand the minimum load, and B2 exceeded this value, thus showing potential as a redesign for additively manufactured building bricks.

TABLE IV
MECHANICAL PERFORMANCE OF THE BRICKS.

Type of brick	Von Mises (*MPa*)		≥ 11.7 MPa
	Mean Values	Deviations	
Vertico & Sika concretes			
Commercial brick	*11.76*	*3.55%*	✓
Brick – B1	*10.43*	*5.09%*	✗
Brick – B2	*14.50*	*3.63%*	✓
Webber 115, Webber 145/2			
Commercial brick	*11.76*	*3.79%*	✓
Brick – B1	*10.91*	*4.80%*	✗
Brick – B2	*14.51*	*3.91%*	✓

IV. CONCLUSIONS

Additive manufacturing offers the redesign of several products since it allows to development of complex shapes with geometric freedom and a high degree of detail. The AEC industry is increasingly using AM as a way to rethink buildings and envelopes. However, there are still many challenges related to including this technology as a basis for this industry. Nature, traditional shapes, and topology optimization, among many others, can inspire geometry. Although, these techniques should be offered to architects, engineers, and designers by developing tools that can be easily integrated. Thus, being inspired by product design guidelines such as VDI 2221 and design thinking may ease AM industrialization in construction. This study proposed a redesign methodology following these guidelines, leading to the development of a building brick including rectangular-shaped internal cells. AM may be coupled with other technologies, such as using PCM, to achieve materials, energy savings, and sustainability in this field.

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