Topography optimization and additive manufacturing in the building and construction industry

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Abstract. A systematic review covering Topology optimization and Additive manufacturing has been conducted. Covering areas such as its application on the building and construction industry and the potential of its mixed-use. The results found shows the increased interest of the research in this area during the last decade and the vast potential of its full application for safety improvements and resource efficiency.

1. Introduction
During the construction of structural components, the best possible configuration is always desired to achieve superior performance characteristics. The architectural design process employs different techniques for this propose, ranging from purely empirical approaches to mathematical methods [1]. The latter being the most relevant for the case of structural optimization.

The optimization processes work to obtain the optimal component dimension, geometry, or material distribution, considering different criteria such as maximizing its rigidity, minimizing stresses, deformations, vibrations, and others. Topological optimization (TO) as a mathematical design tool has been widely used for several years with rapid growth as a research field.

The use of OT methods has spread to different industries with promising results. Nevertheless, in most cases, its potential has been limited because the geometries obtained were impossible or presented significant challenges to be manufactured using traditional construction techniques.

Additive manufacturing (AM) techniques were based on the construction employed successively adding material layers. They have done away with the typical constraints of conventional construction processes allowing the materialization of parts with high geometrical complexity or functional designs without significant cost effects.

The construction industry has been embraced AM as a tool in recent times [2], opening a wide range of application possibilities, including improvements in design flexibility [3] with a reduction in material and labor requirements [4].

This paper presents findings of a systematic review covering TO and AM. It is covering areas such as its application on the building and construction (B&C) industry and the potential of its mixed-use. The results presented are part of a study to identify technologies with potential application during a spatial colonization process.
2. Methodology
The research methodology adopted in this research was a systematic review. Considered an essential scientific research method could be used to analyze, summarize, and convey the conclusions and consequences of large quantities of research publications [5].

For this specific case, the process has been conducted to identify the evolution of Topology Optimization and Additive manufacturing techniques in the construction industry. Two databases were employed, Web of Science and SCOPUS. The reputation of these databases was the decisive factor for this selection.

The critical terms for the search were “Topology optimization”, “Additive Manufacturing”, and “3D printing”. Only English published studies with construction as a focus were considered. A two-stage selection process was executed. During the first stage, a search employed any individual term plus construction was conducted, this phase was used to identify some main trends, close the search period, and to refine the search process. In the second stage, the three terms were used together. The manuscripts found were classified, examined, and reviewed. The relevant information contained was summarized and presented.

3. Results
Overall results of the first stage of the work were presented in table 1.

| Search term                | Scopus | Web of Science |
|----------------------------|--------|----------------|
| Additive Manufacturing     | 888    | 588            |
| 3D printing                | 1299   | 881            |
| Topology Optimization      | 361    | 239            |

Through the last decade, the number of documents having within their scope, the selected research terms have increased significantly. Between the different types of documents available, the most representative were scientific articles be more of the 55%. Its information and results can bring a profound contribution to the body of knowledge for new construction technologies. In figure 1, it is possible to see the distribution by year and type of the found documents.

Figure 1. First stage documents distribution
For the second stage, the number of documents obtained in Scopus and Web of Science was 32 and 26, respectively. Duplicated papers were eliminated. The final analysis was developed with 44 selected documents.

3.1. Topology optimization

The development and application of numerous computer optimization tools were found. Its purpose is the cost or material reduction while attaining a specific design criterion. TO commonly appear as a gradient-based design instrument that establishes where put material is based on the load distribution, stress, and boundary conditions for a goal [6].

3.1.1. Methods. Different TO methods and approaches [7] have been introduced for the work with a continuum structure. These include the density approach [8], [9]; the level set strategy [10], [11]; evolutionary approaches [12]; and several others [13].

Density-based methods form the basis for most recent topology optimization literature because of the degree of sophistication achieved. It represents the optimized structure by a set of density vary values at discrete nodes in the project domain [14]. Between these methodologies, the SIMP (“Solid Isotropic Material with Penalization”) has demonstrated to be very successful and extremely skillful. A full description of this approach can be found in [15].

Adaptations of this along with other methods were used to integrate enhancements or modifications to be applied during the design phases of components to be manufactured using AM techniques such as [16].

3.1.2. Applications. The development of proper applications of TO methods in the construction industry has gained an expanding consideration [17]. Some contributions are Staged construction [18]; Optimized strut-and-tie models for RC members [19]; Reinforced structures [20], [21], [22]; Prestressed girder (Figure 2) [14]; Concrete beams and structures [23], [24]; Dapped beams [25], Building vibration behaviour improvement [26] and Buildings outrigger placement [9].

![Figure 2. Topology optimized design for 3D-print construction. Source [14]](image)

3.2. Additive manufacturing

AM also now as 3D printing is considered an innovative process that could create intricate shape geometries directly from a digital model [27]. The B&C industry have been explored AM [28] in academic [29] and practical applications (Figure 3), primarily focused on demonstrating viability [4].

![Figure 3. AM constructed pillar. Source [30]](image)
AM could allow the development of well custom-built components and inspire intricate and refined design [31]. Its ability to work in an autonomous or semi-autonomous way can reduce the requirement of workforce [28] situation that can be able to generate substantial diminishes on fatalities and injuries that are a severe problem of the B&C industry [32], [33]. Nevertheless, as with any new technology, to harness its full potential and achieve its extensive use, many faces remain.

3.2.1. Processes All the AM categories recognized by the ASTM [34] have a potential application in different aspects of the B&C industry, from architectural representation to full building construction. However, considering only the last case (Large-scale printing) is possible to find process names such as Contour Crafting [35]; Concrete Printing [36]; Freeform construction [23]; Cementitious paste extrusion [37]; Layered extrusion processes [38]; Material deposition method (MDM) [27]; Stick dispenser [39]; Digital construction platform [40]; Flow-based fabrication [41]; Mesh-mould [27]. Figure 4 shows an image of the concrete printing process.

![Concrete Printing Process](image)

**Figure 4.** Concrete printing process. Source [42]

3.2.2. Materials Limited materials are now available for AM in the B&C industry [43]. One of the major faces is the conversion of existing high-quality concretes to printable materials. Concrete or cement-based are considered as intricate material with a non-homogeneous composition. Intensive research has recently been done on the production and use of admixture to achieve the desired material performance [44], [45], [46].

4. Conclusions
Additive manufacturing and Topology optimization have a vast potential of application on the building and construction industry.

The use of these combined techniques could bring the industry's most significant benefits in terms of resource economy and safety.

A proper integration route for AM and TO is essential to take full advantage of its potential.

Limited materials are now available for AM in the B&C industry, but intensive research is happening in this knowledge area.

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