Review

Bird’s Eye View on Lattice Structures: Design Issues and Applications for Best Practices in Mechanical Design

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Abstract: Lattice structures for engineering applications are patterns of unit cells designed to make a larger functional structure. Research on lattice structures ranges in many fields, from mechanical characterization and cell and pattern designs in respect of their applications, to the manufacturing process and its final shape control. From the manufacturing point of view, some kinds of lattice structures can be infeasible when approached with traditional manufacturing methods. It may offer an inevitable limitation of their adoption. However, advancements in Additive Manufacturing (AM) have solved this manufacturing issue to a great extent, allowing to obtain major complexity of the cells that can be achieved. The topology, shape of the unit cell, and the characteristics of its replication pattern allow us to obtain many kinds of structures in respect of the different engineering requirements and manufacturing constraints. Nevertheless, the necessity of new or dedicated CAD-CAE approaches arises to manage the domains of multiscale modeling. These are some of the advantages and disadvantages that may arise while approaching the design of a component using lattice structures. The aim of this paper is to provide an overview that integrates the most recent applications of lattice structures with their related design and manufacturing issues so that, from a practical design point of view, any state-of-the-art improvements may be established in respect of the related field of applications. In this article, engineers and researchers may find a practical summary of the capabilities and processes of lattice structures that are currently available from a design and development point of view.

Keywords: lattice structures; cellular structures; functionally graded materials; TPMS; design methodologies; additive manufacturing

1. Introduction

A lattice structure is made by a unit cell that is repeated in the space, making a larger functional structure; thus, it is a peculiar kind of cellular structure. The basic idea of cellular structures evolved from natural organic structures such as bamboo, bone, cork, etc. For the very first time, the concept of cellular structures was introduced by Gibson and Ashby [1,2]. Initially, they classified cellular structures into foam (open cell and closed cell, Figure 1a,b) and honeycomb. Foam’s cell shape and pattern are usually defined by random distributions, while the honeycomb structure has a regular 2D hexagonal unit cell and the cell walls are uniformly oriented in the space (as shown in Figure 1c). In open-cell foam, the cells are not totally enclosed by their walls, while in closed-cell foam, the cells are entirely enclosed by their walls. Despite these differences, the component is always defined from a micro/mesoscale cell, replicated to fill the overall macroscale volume. However, the cellular structures were later classified [3,4] into three main categories: foam, honeycomb, and lattice.
According to the literature, in many applications, lattice structures have been found to be superior to their other cellular counterparts, such as foam and honeycomb structures. A more in detail strength-to-weight ratio and mechanical performance, such as energy absorption or compliance, is generally better due to the tailored shape of the cell and the replication pattern [6,7]. Moreover, they can support functional designs, such as heat exchangers or fluid conveyors, as demonstrated in [8]. More recently, taking inspiration from natural organic structures such as bones and plant stems, the concept of graded densities increased the spread of lattice structures, for example, being used to optimize load distributions [9,10]. It also furthers the evolution towards multigrade lattice structures, coupled with different materials. From this, the concept of multigrade and multifunction lattices arises. These are the solutions in which not only the type of unit cells but also the cell’s density and materials are distributed to gain a specific performance or function. Multigrade lattice structures have numerous applications, i.e., to enhance stiffness [11], to increase energy absorption capability [12–17], to improve thermal exchange efficiency [18,19], to tailor specific behaviors such as a negative Poisson’s ratio [20–22], etc.

From the manufacturing point of view, Additive Manufacturing (AM) is often considered as a specific technology to manufacture lattice structures; indeed, the capability of reproducing specific cell designs and distribution through AM increases the fields of investigation pertaining to lattice structures in the respect of foams. Nevertheless, foams obtained by blowing agents (in batch foaming, extrusion, or injection molding) may have a superior reliability concerning the mechanical characteristics since the AM interlayer interfaces may present delamination and, thus, crack propagation [23]. Besides this aspect, the advancements in AM with multigrade materials for lattice structures have gained immense popularity, providing an extraordinary performance and array of functions [24,25].

Due to these promising characteristics, lattice structures have been extensively studied and they are still undergoing rigorous research to support numerous industrial applications. Research on lattice structures ranges in many fields, such as mechanical characterization, manufacturing processes and its final shape control, and cell and pattern designs in respect of their applications.

This paper aims to provide a bird’s eye view concerning the mechanical research of lattice structures, linking their geometrical characteristics with the type of applications and related design practices, considering both manufacturing and the necessity of new or dedicated CAD-CAE approaches to manage the domains of multiscale modeling.

The final goal is to highlight a general perspective for addressing the design workflow of lattice structures and support engineering best practices in the design of these kinds of solutions.

For this, in Section 2, the lattice structure classification is reviewed and documented in terms of cell, replication pattern, and mechanical characteristics. In Section 3, applications related to the main engineering fields with respect to the types of lattice structures are presented. Then, in Section 4, the CAD-CAE design approach is discussed, together with the geometrical characteristics of lattice structures and their major manufacturing issues. Finally, in Section 5, basic conclusions and perspectives are suggested.
2. Lattice Classification

According to [23], lattice structures may be classified based on:

- The unit cell’s characteristics, which include topology, cell’s element geometry, and cell’s size.
- The characteristics of the cell’s replication pattern.

However, in [26,27], the classification of the lattice structure has been discussed in more detail; therefore, the latest classification of lattice structure can be shown as Figure 2.

![Figure 2. Classification of lattice structure.](image)

2.1. Unit Cell Characteristics

A topology-based classification defines whether the cells are closed or open and how many cells’ faces are open, while a cell’s element geometry, according to [2], distinguishes between cells made of struts and cells made of plates or shells, introducing a structural behavior classification of the cells. A cell’s element geometry includes a geometrical definition of the structural elements (sections, number of edges, . . .) [6,7,23,28], and the size, including all the dimensional elements that define a cell (e.g., section size and axial length for struts, length, width, and thickness for plate/shell). The cell’s element geometry, indeed, may also constrain the topology of the cell (e.g., strut cells are always open, shells and plates may be open with different geometrical shapes). Concerning the cell’s size, the distinction between homogeneous and heterogeneous defines whether the structural elements of the cell are constant or not. Figures 3 and 4 show an overview of strut-based and surface-based lattice cells, respectively.

Concerning strut-based unit cells, Simple Cubic (SC), Body-Centered (BC), and Body-Centered Cubic (BCC) are derived from the same cubic cell, just with an increasing number of beams [23,29–31]. The Octet Truss (OT) cell comes from the face-centered cell [32]. Other frequently used cells are the modified Gibson–Ashby (GA) and the modified Wallach–Gibson (WG) cells [6,7,23,28]. Figure 3h shows an example of a re-entrant cell.
Figure 3. Beam Lattice (generated with nTop and the colored lines show the 3D reference system useful for comparison): (a) Simple Cubic Cell; (b) Body Centered Cubic Cell; (c) Face Centered Cubic Cell; (d) Diamond Cell; (e) Fluorite Cell; (f) Octet Cell; (g) Truncated Octahedron Cell; (h) Re-entrant Cell; (i) Truncated Cube Cell; (j) Kelvin Cell; (k) Iso Truss Cell; (l) Weaire–Phelan Cell.

Figure 4. Surface-based lattice (generated with nTop and the colored lines show the 3D reference system useful for comparison): (a) Simple Cubic Foam Cell; (b) Body Centered Cubic Foam Cell; (c) Face Centered Cubic Foam Cell; (d) Hexagonal Honeycomb Cell; (e) Triangular Honeycomb Cell; (f) Re-entrant Honeycomb Cell; (g) Schwartz Cell; (h) Gyroid Cell; (i) Diamond Cell; (j) Split-P Cell; (k) Lidinoid Cell.
It is an auxetic cell designed to present a negative Poisson’s ratio, which means that the cell enlarges when stretched and contracts when compressed [33–36].

Concerning surface-based unit cells, we can distinguish between plate and shell cells, and, more generally, surface-based cells like Triply Periodic Minimal Surface (TPMS). In [37], according to Gibson, the plate cells were investigated connecting some struts of Figure 3 with plates, as shown in Figure 4a–c. These solutions, although may be replicated as periodic and regular, are often considered a type of closed foam, as commented in [38]. A honeycomb lattice [28], shown in Figure 4d–f, may have unit cells that are hexagonal or triangular; recently, the re-entrant configurations have also been studied.

Triply Periodic Minimal Surfaces (TPMSs) are being widely investigated. They are bio-inspired cells with boundary surfaces with a zero-mean curvature at every point [39,40]. TPMSs are relevant as functionally graded structures since their geometric characteristics allow them to reach different surface-related properties (e.g., manufacturability, fluid permeability, electrical and thermal conductivity). According to the procedure adopted to model them, they can be classified as skeletal and sheet TPMSs. In the first case, a volume is trimmed by the TPMS and the remaining part is thinned (skeletonized) with an assigned thickness. In the second case, the TPMS represents the shell sheet that is subsequently thickened.

**TPMS Formulation**

From a mathematical point of view, a TPMS is an infinite surface, periodic along three mutually orthogonal directions, which satisfies the following conditions:

\[
\begin{align*}
H(x, y, z) &= 0 \\
H &= \frac{k_1 + k_2}{2}
\end{align*}
\]  

(1)

where \(k_1\) and \(k_2\) stand for the principal curvatures of the surface at a general point \(P\). Many authors studied the theoretical formulations of TPMS, starting from different mathematical points of view. In [39], the level set method, an approach applied in mechanical engineering to optimize topology in accordance with structural requirements, is adopted to study five TPMSs, namely Primitive, Gyroid, IWP, Diamond, and Fisher–Koch. Assuming that a TPMS may be described by a sum of Fourier terms and that its leading term is the basis function of the TPMS, i.e., \(\varphi(x, y, z)\), the TPMS can be achieved as iso-level curves:

\[\varphi(x, y, z) = \text{const}\]  

(2)

Subjected to Equation (1). Equations (3)–(5) show three formulations achieved according to such reasoning, reported in Figure 4g–i.

Schwartz primitive:

\[\varphi(x, y, z) = (\cos x) + (\cos y) + (\cos z)\]  

(3)

Schwartz diamond:

\[\varphi(x, y, z) = (\cos x)(\cos y)(\cos z) - (\sin x)(\sin y)(\sin z)\]  

(4)

Gyroid:

\[\varphi(x, y, z) = (\sin x)(\cos y) + (\sin y)(\cos z) + (\sin z)(\cos x)\]  

(5)

where:

\[x = 2\pi \frac{X}{L_x},\]

\[y = 2\pi \frac{Y}{L_y},\]

and

\[z = 2\pi \frac{Z}{L_z}.\]  

(6)
The $L_x$, $L_y$, and $L_z$ are the unit cell size in the $X$, $Y$, and $Z$ directions. $x$, $y$, and $z$ are the periodicities, while $X$, $Y$, and $Z$ are the cell’s repetitions.

2.2. Characteristics of the Cell Replication Pattern

Characteristics of the replication pattern are concerned with the cell’s connection, orientation, and density in the space, as discussed in [7,41,42]. It also pertains to the cell size in the sense that the cell’s length may also change along the replication pattern randomly or according to a gradient as a request of the design intent (e.g., functionally graded lattice structures) [43–46].

Replication patterns can be:

- Regular.
- Pseudo-regular.
  - Hybrid,
  - Warped (or gradient) by cell size,
  - Warped (or gradient) by thickness,
  - Conformal.
- Stochastic.
  - Random by cell size,
  - Random also by thickness.

In a regular replication pattern, no changes regarding the unit cell characteristics occur at all (Figure 5). Hybrid patterns include different unit cells that may also have different geometric characteristics (Figure 6). They can be considered as part of pseudo-regular patterns that provide several replications based on the variation in the unit cell’s size.

**Figure 5.** Examples of regular replication patterns (generated with nTop): (a) Kelvin Cell; (b) Re-entrant Cell; (c) Re-entrant Honeycomb Cell; (d) Split-p Cell.

**Figure 6.** Examples of hybrid replication patterns achieved by changing the unit cells (generated with nTop): (a) BCC Lattice + Diamond Lattice + FCC Lattice; (b) BCC lattice + Gyroid TMPS.
Pseudo-regular patterns also include warped (gradient) and conformal structures (Figure 7). The gradient by cell size is a replication pattern that provides a structure in which the unit cell’s size varies gradually along a specified direction, while the thickness of the elements remains the same (Figure 7a). In the case of the gradient by thickness, the structure maintains a constant cell size, but its thickness is changed (Figure 7b). Conformal lattice structures consist of cells changing in length and shapes non-homogeneously, so that the replication pattern may follow the boundaries of the part (Figure 7c) [47,48].

![Image of pseudo-regular pattern replications](image)

**Figure 7.** Examples of pseudo-regular pattern replications (generated with nTop): (a) BCC cells with gradient by thickness; (b) BCC cells with gradient by cell size; (c) Simple cubic cells conformal.

In stochastic patterns, the cell size varies randomly, while the thickness remains the same. However, in stochastic random patterns, the thickness varies randomly or along a gradient throughout the structure (Figure 8).
2.3. Mechanical Behavior

The mechanical behavior of cellular materials is affected by the micro/mesoscale characteristics (unit cell and replication pattern), in addition to the macroscale topology and shape of the overall component [49,50]. This means that the local behaviors determine the global mechanical response and its related performance. Based on their local mechanical response, the lattice structure is generally classified into [51]:

- **Bending dominated.**
- **Stretch dominated.**

Bending-dominated structures react locally with a bending deformation. This makes them extremely useful (such as compliant structures) for applications related to mechanical energy absorption, especially in crashworthiness design [52,53]. Stretch-dominated structures experience a stretch deformation under the action of a uniaxial compression or tension within their material linear elastic limit (e.g., yielding strength, ultimate strength). This makes them useful for a lightweight design without losing the global stiffness of the component.

The Maxwell stability criterion may help to determine the local behavior of a truss-based cell by its Maxwell number \( M \):

\[
M = s - 3n + 6 \tag{7}
\]

where \( s \) is the number of struts, \( n \) is the number of joints in the unit cell, and 6 is the \( d.o.f. \) in cases of three-dimensional structures. When \( M \) equals zero or is greater than zero, it means that the isostatic or over-constrained solutions undertake a stretch-dominated category. The condition of \( M \) as less than zero means that the structure is a mechanism assumed to weld the joints (as it will be in a real lattice cell) and it undertakes a bending-dominated category.

According to this reasoning, the bending-dominated cells are BCC and Kelvin structures, while honeycomb (if axially loaded) and Octet cells are stretch dominated (concerning...
the application of $M$ to the honeycomb, it is worthwhile to remember that shell-based cells are derived from the truss-based cells, assuming the cells are closed by their walls).

In [34], the classification between stretch- and bending-dominated structures is enriched by proposing a third class, named “programmable active”, able to actively merge the two categories. Active structures are functionally graded materials, such as auxetic cells, which have the ability to switch their behavior from stretched dominated to bending dominated. This is extremely suitable for crashworthiness designs when the defined impact loads may activate the plastic bending.

According to the Gibson and Ashby power criterion [51], the elastic modulus of the unit cell can be calculated with the help of the following equations:

For a bending-dominated lattice,

$$\frac{E^*}{E_s} = C \left(\frac{\rho^*}{\rho_s}\right)^2$$  \hspace{1cm} (8)

For a stretch-dominated lattice,

$$\frac{E^*}{E_s} = C \left(\frac{\rho^*}{\rho_s}\right)$$  \hspace{1cm} (9)

where $E^*$ is the elastic modulus of the cellular structure and $E_s$ is the elastic modulus of the equivalent solid. Similarly, $\rho^*$ is the density of the cellular structure and $\rho_s$ is the density of the equivalent solid. $C$ is the Gibson and Ashby constant which depends on the unit cell’s topology and is determined by experimental tests. From Equations (8) and (9), the modulus density chart of the lattice cells can be defined to assess performance of the cells in respect to the ideal behaviors. In addition, similar equations are available for finding the strength density chart.

Lattice structures made by AM are currently studied from the resistance point of view to validate both the structures and the technological process. More in detail data are necessary to assess the repeatability of the stress–strain behavior to be used in the integrated product–process design. The AM discontinuities at a small scale may penalize the fatigue behavior, as discussed in [55]. In the literature, many other examples of mechanical characterization on lattice structures are provided. Ref [56] studies the compression and three-point bending resistance of 3D Kagome lattices, while [57] provides a comparative study of the auxetic cells that are systematically compared in terms of the Poisson ratio, maximum volume or area reductions, and the equivalent Young’s modulus by CAD-CAE tools. In [40], five TPMS structures are characterized from a dynamic point of view with the Hopkinson bar, finding the strain-rate effect on the stress–strain response. This result is also discussed in terms of the strain-rate sensitivity of the base material and the accuracy of the AM process.

3. Applications

Querying the Scopus database for research fields and applications related to lattice structures published in journals in the last decade, an exponential trend can be clearly seen, which is also confirmed by provisional data from 2023. In detail, Figure 9a shows relative percentage bars for five main topics related to specific technological and design fields (additive manufacturing, lightweight design, energy absorption, biomedical, and heat dissipation) and two emerging keywords related to functionally graded materials that fit the lattice structure classification we made, TPMS and Auxetic. Figure 9b shows the overall number of papers per topic found by the queries. As predicted, TPMS and auxetic are still limited in respect of AM (the most populated topic), lightweight, and energy absorption design. In the middle of the rank, there are biomedical applications and studies, partially related to TPMS, and heat dissipation, which also includes heat exchangers and sinks.
Being part of the class of cellular materials, lattice structures may be adopted to design functional structures. In the respect of foams, lattice structures have more characteristics to be tailored to both the meso and macroscale level, according to the description made in Section 2. A design optimization suitable to fine tune these characteristics enables better performances, as highlighted, for example, in [44], discussing the lightweight design. According to this, one of the most recent overviews concerning lattice structure applications, presented in [58], classifies the applications in respect of the relevant design properties that the lattice structure may help to achieve.

The ability to tailor the stiffness of a structure via the cell topology and pattern [59] enables control of the stress and strain for energy absorption, both in static and dynamic conditions at a high strain rate [60]. This makes them appropriate for crashworthiness designs and for controlling shock absorption, vibration, and acoustic noise, all of which are useful for the automotive, aerospace, ergonomics, ballistics, packaging, robotics, and tool manufacturing fields [12,13,16,17,20,38,61]. According to [33,62], Kelvin cells must be cited as structures derived from basic beam cells with the best performance for dampening vibrations.

A clear example of how the lattice structure may be tailored in respect of the assigned design requirements is provided by auxetic lattice structures. They can realize structures with a negative Poisson’s ratio, which could be utilized in the aerospace sector for the
design of morphing wings for next generation aircrafts [63–65]. Similarly, in biomedical applications, such as bones based on TPMS cells, they can tailor structures, making them suitable to match bone stiffness, surface roughness, and material compatibility for bone growth, as demonstrated in [66,67].

Another class of applications is related to their capability of achieving a high surface/volume ratio or proper thermal conduction characteristics that make the lattice structures suitable for thermal insulation, heat pipe wicks, exchangers, and sinks. In [68], applications related to thermal systems are reviewed and encouraged, thanks to AM advancements. They involve both metallic and non-metallic lattice structures. Heat transfer media made of lattice structure increases the efficiency of the process, as demonstrated in [69].

Concerning the correlation between applications and the characteristics of the lattice structures according to unit cells and replication patterns, Table 1 provides an overview of references in terms of the industrial sectors and related applications.

### Table 1. Applications: overview by field of expertise, lattice structure classification, and useful references.

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Unit Cell/Replication Pattern</th>
<th>Applications</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerospace Engineering</td>
<td>• BCC</td>
<td>• Heat Exchanger</td>
<td>[18,70–76]</td>
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<tr>
<td></td>
<td>• Auxetic</td>
<td>• Wings</td>
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<td></td>
<td>• Rhombic</td>
<td>• Gas Turbine Fan Blades</td>
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<td>• Chiral</td>
<td>• Airfoil</td>
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<td></td>
<td>• Honeycomb</td>
<td>• Drone Structure</td>
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<td>• Pyramidal</td>
<td>• Satellite Structure</td>
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<td>• Rocket Body</td>
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<td>• Landing Gear</td>
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<tr>
<td>Biomedical Engineering</td>
<td>• Diamond Cubic</td>
<td>• Hip Implant</td>
<td>[77–86]</td>
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<td></td>
<td>• Stochastic</td>
<td>• Orthopedic Implant</td>
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<td></td>
<td>• Octet-truss</td>
<td>• Bone Scaffold</td>
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<td>• Tetrahedral</td>
<td>• Femoral Stem</td>
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<td>• BCC</td>
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<td>• TPMS</td>
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<td></td>
<td>• Honeycomb Lattice</td>
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<tr>
<td>Automotive</td>
<td>• Honeycomb</td>
<td>• Crash Box</td>
<td>[87–92]</td>
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<tr>
<td></td>
<td>• Truss-based</td>
<td>• Bumper</td>
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<tr>
<td></td>
<td>• TPMS</td>
<td>• Engine Hood</td>
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<td></td>
<td>• Auxetic</td>
<td>• Crash Absorber</td>
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<td>• Chassis Frame</td>
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<td></td>
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<td>• Heat Exchanger</td>
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<td>• BCC</td>
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<tr>
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<td>• Auxetic</td>
<td>• Military Seat Shock Panel</td>
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<td>Mechanical Engineering</td>
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<td></td>
<td>• Cubic</td>
<td>• AM Volume Infills</td>
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<td></td>
<td>• FCC</td>
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<td></td>
<td>• TPMS</td>
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Table 1. Cont.

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<thead>
<tr>
<th>Sectors</th>
<th>Unit Cell/Replication Pattern</th>
<th>Applications</th>
<th>References</th>
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<tbody>
<tr>
<td>Civil Engineering: Building</td>
<td>• BCC</td>
<td>• Canton Tower</td>
<td>[107–109]</td>
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<td>Construction</td>
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<td>• Beijing National Stadium</td>
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<td></td>
<td>• Stochastic</td>
<td>(Bird’s Nest)</td>
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<tr>
<td></td>
<td>• BCC</td>
<td>• The Atomium</td>
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4. Design and Manufacturing Issues

In this section, the manufacturing issues, together with design approaches and tools, are highlighted in order to offer an overview of how to build the lattice structure components in respect of the application’s requirements.

From a design point of view, unit cell selection is strongly affected by the functional requirements that need to be accomplished; but it is also constrained by the manufacturing feasibility. The manufacturing feasibility may be related to the type of structure (according to the classifications of Section 2) or to process limits, such as the range of accuracy, lengths, necessity of post-processing, etc. According to this, Tables 2 and 3 show the manufacturing methods versus the base materials and major limitations, together with references where such limitations are exploited. In detail, Table 2 refers to the traditional manufacturing processes and Table 3 refers to AM processes.

Table 2. Correlation table among traditional manufacturing methods, base material, limitations, and related references.

<table>
<thead>
<tr>
<th>Manufacturing Method</th>
<th>Base Material</th>
<th>Issues</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Foaming</td>
<td>Metals</td>
<td>• Cell Replication Pattern: Only stochastic structure can be obtained.</td>
<td>[110,111]</td>
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<tr>
<td>Investment Casting</td>
<td>Metals</td>
<td>• Low accuracy for fine structures.</td>
<td>[112–114]</td>
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<tr>
<td></td>
<td></td>
<td>• Long production time.</td>
<td></td>
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<tr>
<td>Stamping Forming</td>
<td>Metals</td>
<td>• Cell’s characteristics.</td>
<td>[115,116]</td>
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<tr>
<td></td>
<td></td>
<td>• Post processing is required.</td>
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<td></td>
<td></td>
<td>• Difficult to produce fine structures.</td>
<td></td>
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<tr>
<td>Interlocking Grid Assembly</td>
<td>Metals</td>
<td>• Cell’s characteristics.</td>
<td>[117–119]</td>
</tr>
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<td></td>
<td>Composites</td>
<td>• Difficult to produce fine structures.</td>
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<td>Polymer Fibers</td>
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<tr>
<td>Extrusion Wire Cutting</td>
<td>Metals</td>
<td>• Cell’s characteristics.</td>
<td>[120]</td>
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<tr>
<td></td>
<td></td>
<td>• Costly processes.</td>
<td></td>
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<td>Lap Assembly</td>
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<td></td>
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<td>Wire-Woven Method</td>
<td>Metals</td>
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<td>[121–123]</td>
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<tr>
<td></td>
<td></td>
<td>• Post processing is required.</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Correlation table among Additive Manufacturing (AM) methods, base material, limitations, and related references.

<table>
<thead>
<tr>
<th>AM Method</th>
<th>Base Material</th>
<th>Issues</th>
<th>References</th>
</tr>
</thead>
</table>
| Binder jetting (BJ)                     | Metals, Ceramics, Polymers | • Part shrinkage 2–3%  
• Low accuracy and tolerance | [124–126]        |
| Cold Spray Additive Manufacturing (CSAM)| Metals, Ceramics   | • Loss of ductility due to plastic deformation  
• Post processing | [127–129]        |
| Direct Energy Deposition (DED)          | Metals, Ceramics   | • Low resolution  
• Poor surface finish  
• Costly | [130–132]        |
| Direct Ink Writing (DIW)                | Ceramics, Metals, Slurries, Polymers, Sol-gel inks | • Fine surface finish, in cases of ceramics | [133–135]        |
| Fused Deposition Modeling (FDM)         | Metals, Thermoplastics, Wax | • Slow Speed  
• Low Accuracy | [136–138]        |
| Liquid Metal Additive Manufacturing     | Metals            | • Melting and cooling of the printing material influencing the final geometry | [139–141]        |
| Laminated Object Manufacturing (LOM)    | Papers, Plastics, Metals | • Poor surface finish | [142–144]        |
| Powder Bed Fusion (PBF)                 | Metals, Ceramics, Thermoplastics, Wax | • Volumetric Expansion  
• Low accuracy and tolerance | [145–147]        |

Generally speaking, traditional manufacturing methods have severe limitations concerning the type of cells that can be built. In particular, a limited set of cells may be obtained through joining the manufactured details achieved on relevant plates (e.g., honeycombs are manufactured by joining hexagonal cells between plates). In some cases, the replication patterns may be limited (e.g., direct foaming). It is clearly shown how AM processes may overcome the limit on the unit cell characteristics. Traditional manufacturing processes are mostly limited to base materials (mostly available in metals), few types of unit cells, mandatory post processing, high production times, and the unavailability of fine structures. However, AM solutions are limited to mandatory post processing (in the most cases), high production times, weak performance against fatigue loading, low aesthetic, build direction, residual stresses, support/sacrificial structures, etc. Particularly, the build direction/orientation during the AM should be meticulously defined to avoid volumetric expansion/geometrical errors and to minimize the residual stresses and the support volume/sacrificial supports [148,149].

According to the literature [150–155], researchers have mostly defined development workflows for the design and manufacturing of lattice structures separately. Most of these
development workflows are based on very few basic requirements that pertain only to the lattice structure’s design and the manufacturing process, often without considering the overall optimization requirements of weight reduction, assembly efforts, reliability, post processing issues regarding mechanical performance (in general), support structure removal in the case of AM, and so on.

Pattern replications may be defined by topological optimization [156] to improve the component performances, also considering other manufacturing constraints, including:

- For AM: working volume, support and infill design, post processing.
- For traditional manufacturing processes: die design, extra and complex tooling/attachment, multiple machining/manufacturing processes, precise manufacturing process control, complex assembly/bonding process, post processing and/or set up by other design criteria such as aesthetics, assembly, etc.

In [156], AM lattices for biomedical applications related to implant design are studied and three design workflows are discussed to optimize this kind of design. In any case, the micro/meso scale of the cell must be replicated at the macro scale to fulfill the component volumes.

From the CAD modeling point of view, it is computationally expensive, often requiring the adoption of dedicated tools and/or a change in the modeling approach. Table 4 shows a summary of current tools available to support the CAD-CAE development of known lattice structures. Only a few of them provide the opportunity for obtaining a diversity of lattice shapes and design freedom.

Table 4. Three-dimensional modeling of lattice structures.

<table>
<thead>
<tr>
<th>Design Tools</th>
<th>Software</th>
<th>Lattice Type</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAD Software/</td>
<td>Solid Works</td>
<td>Beam Lattice</td>
<td></td>
</tr>
<tr>
<td>Numerical Solvers</td>
<td>nTopology</td>
<td>TPPS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Optistruct</td>
<td>Honeycomb</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inspire</td>
<td>Voronoi</td>
<td>[152,157–172]</td>
</tr>
<tr>
<td></td>
<td>Rhinoceros</td>
<td>Auxetic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grasshopper</td>
<td>Conformal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fusion 360</td>
<td>Gradient Lattice</td>
<td></td>
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<tr>
<td></td>
<td>PTC Creo</td>
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<td></td>
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<tr>
<td></td>
<td>Netfabb</td>
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</tr>
<tr>
<td></td>
<td>Materialize</td>
<td></td>
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<tr>
<td></td>
<td>Free CAD</td>
<td></td>
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<tr>
<td></td>
<td>Ansys</td>
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</tbody>
</table>

Special Tools
- MS Lattice
- Flatt Pack
- TPMS

In cases of cells defined by shell elements, many CAD solutions (such as nToplogy, Rhinoceros, Surface Design in Catia, . . .) adopted Implicit CAD Modelling (ICM) to vary the cell characteristics and the pattern distribution analytically. This enables the driving of results via optimization criteria since, through ICM, the geometry is directly described by a mathematical equation. Although ICM may produce formulas not physically realistic (e.g., non-manifold solutions), in cases of lattice structures, it can use the data points to influence the design with instant changes and, therefore, assists the design with any change in the geometry [104,175]. Through a field-driven design, ICM may simplify the pattern definitions for conformal, stochastic, and hybrid structures by utilizing a scalar field that represents the unit cell replication as a weight of the ICM set of data points. Changes of the field drive the geometry and alter the characteristics of the pattern. Commonly, it helps to optimize the lattice structure based on the stress field [104].
In [176], a hybrid geometric modeling method is proposed in which the selected unit cell is replicated using a voxelization approach for the complex volume being fulfilled, through geometrical functions which are suitable for describing the cell. Generally, the computation loop includes one or more steps for filling the inner volume with cells and additional steps to constrain the boundary surface. It enables good transferability to the CAE analysis, closing the information loop between CAD modeling and FEA analysis which often limits the actions of the designer when she/he adopts commercial software. Moreover, it can provide both regular and stochastic replications in conformal configurations thanks to a Voronoi-based approach [177,178]. In [179], a NURBS-Free Form Deformation (FFD) approach is proposed and validated by FEA to build and optimize conformal truss-based lattice structures. Other methods to build conformal lattices are the Twin Curve Division Method (TCD), Arc Division Method (AD), Curvature Division Method (CD), and NURBS Free Form Deformation Method (NFFD).

5. Conclusions

This paper provides some insights into the design capabilities of lattice structures, with subsequent achievable properties in the context of engineering requirements and applications, with a wide range of materials from metal to plastic. For a few decades, researchers have extensively worked to unfold the unique characteristics of lattice structures, such as auxetic structures, negative thermal expansions, active stiffness, etc. These functional properties are derived from lattice cell characteristics; for this reason, the paper linked design and manufacturing issues, such as replication patterns, cell mechanical response, and manufacturability, to the most relevant engineering applications found in the research literature. Moreover, to provide the design practice point of view, CAD-CAE issues related to their modeling and optimization were also discussed.

This review also highlighted that the lattice structures benefit many engineering sectors in the context of engineering requirements, including lightweight structures, energy absorption structures, conduction/convection heat management, sound/vibration energy minimization, electromagnetic wave shielding, biomedical bone implants, etc. However, based on the above discussions, the following few recommendations are furnished for future research work:

- In order to investigate the mechanical properties of a structure derived from the multiscale properties of the component(s) and from mesoscale cell characteristics, proper functional behavior may be tailored. As such, a CAD-CAE approach may massively help this study by virtual testing.
- CAD-CAE approaches are also affected by the multiscale domains involved in the problem, with increasing computational costs. This provides impetus to adopt new modeling approaches, such as Implicit Geometric Modeling and/or homogenization techniques for CAE analyses.
- In the case of AM, the mechanical characteristics related to stress–strain curves must be investigated and validated to distinguish between the lattice structure properties and AM setup conditions.
- Metallic AM lattice structures suffer with fatigue loads due to the limited process conditions and/or setup. In addition, the post processing treatments may be infeasible due to the complexity of the structures. Therefore, a suitable workflow engulfing all of the design, manufacturing, and post processing requirements may be defined in order to minimize these concerns and facilitate the functional requirements of the lattice structures.
Author Contributions: Conceptualization, F.C. and A.A.; methodology, A.A., F.C. and M.B.; software, A.A.; validation, L.B. and M.B.; formal analysis, A.A., F.C., M.B. and L.B.; investigation, A.A., L.B. and M.B.; resources, A.A., L.B. and M.B.; data curation, M.B. and A.A.; writing—original draft preparation, F.C. and A.A.; writing—review and editing, L.B. and M.B.; visualization, A.A., F.C., M.B. and L.B.; supervision, F.C.; project administration, F.C.; funding acquisition, F.C. All authors have read and agreed to the published version of the manuscript.

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List of Symbols and Acronyms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\phi(x, y, z)$</td>
<td>Basis Function of TPMS</td>
</tr>
<tr>
<td>$L$</td>
<td>Unit Cell Size</td>
</tr>
<tr>
<td>$X, Y, Z$</td>
<td>Cell’s Repetition</td>
</tr>
<tr>
<td>$s$</td>
<td>Number of Struts</td>
</tr>
<tr>
<td>$E^*$</td>
<td>Elastic Modulus of the Cellular Structure</td>
</tr>
<tr>
<td>$\rho^*$</td>
<td>Density of the Cellular Structure</td>
</tr>
<tr>
<td>$C$</td>
<td>Gibson &amp; Ashby Constant</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>SC</td>
<td>Simple Cubic</td>
</tr>
<tr>
<td>BCC</td>
<td>Body-Centered Cubic</td>
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<tr>
<td>OT</td>
<td>Octet Truss</td>
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<tr>
<td>TPMS</td>
<td>Triply Periodic Minimal Surface</td>
</tr>
<tr>
<td>ICM</td>
<td>Implicit CAD Modeling</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>TCD</td>
<td>Twin Curve Division Method</td>
</tr>
<tr>
<td>CD</td>
<td>Curvature Division Method</td>
</tr>
<tr>
<td>NFFD</td>
<td>NURBS Free Form Deformation Method</td>
</tr>
</tbody>
</table>

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