Proposal of a standard for 2D representation of bio-inspired lightweight lattice structures in drawings

Published Version:
Bacciaglia A., Ceruti A., Liverani A. (2020). Proposal of a standard for 2D representation of bio-inspired lightweight lattice structures in drawings. PROCEEDINGS OF THE INSTITUTION OF MECHANICAL ENGINEERS. PART C, JOURNAL OF MECHANICAL ENGINEERING SCIENCE, 236(18), 10051-10062 [10.1177/0954406220951595].

Availability:
This version is available at: https://hdl.handle.net/11585/769377 since: 2024-05-29

Published:
DOI: http://doi.org/10.1177/0954406220951595

(Article begins on next page)

Design

Institution of MECHANICAL ENGINEERS

Journal of MECHANICAL ENGINEERING SCIENCE

Proc IMechE Part C:
J Mechanical Engineering Science
2022, Vol. 236(18) 10051–10062

DOI: 10.1177/0954406220951595
journals.sagepub.com/home/pic
SAGE

Proposal of a standard for 2D representation of bio-inspired lightweight lattice structures in drawings

Antonio Bacciaglia, Alessandro Ceruti and Alfredo Liverani

Abstract

The interest of industrial companies for the Additive Manufacturing (AM) technology is growing year after year due to its capability of producing components with complex shapes that fit industrial engineering necessities better than traditionally manufactured parts. However, conventional Computer-Aided Design (CAD) software are often limited for the design and representation of complex geometries, especially when dealing with lattice structures: these are bio-inspired structures composed of repeated small elements, called struts, which are combined to shape a unit cell that is repeated across a domain. This design method generates a lightweight but stiff component. The scope of this work is to analyse the problem of the lattice structures representation in 2 D technical drawings and propose some contributions to support the development of Standards for their 2 D representation. This work is focused on the proposal of rules useful to represent such hierarchic structures. Python language and the open-source software FreeCad™ are used as a software platform to evaluate the suitability and usability of the proposed representation standard. This is based on simplified symbols to describe complex lattice structures instead of representing all the elements which constitute the lattice. The standard is thought to be used in technical 2 D drawings where assemblies are represented and lattice components are used (e.g. parts assembly, maintenance, parts catalogues). A case study is included to describe how the proposed standard could be integrated into a 2 D assembly drawing, following technical product documentation production typical workflow.

Keywords

Additive manufacturing, lattice structures, design, drawing standards, ISO standards

Date received: 31 January 2020; accepted: 16 July 2020

Introduction

Nowadays Additive Manufacturing (AM) is extremely appealing for designers thanks to several advantages such as time reduction in the design-to-manufacturing cycle, reduction of parts number with the following reduction of bolted connections or welding, and capability to produce complex geometries in one part. Complex 3 D components with bio-inspired efficient structures can be easily produced by adding material layer by layer, in contrast to traditional manufacturing processes based on chip removal, or casting. One of the major topics investigated by literature in this field is the high freedom of shaping guaranteed by AM, characterized by high customization, design flexibility. All these issues can be summarized with the expression: "What You See Is What You Build".[1] This is in contrast with traditional machining processes where a lot of manufacturing restraints should be kept into account while designing a part due to technological issues. To exploit the AM potentials, engineers must change the way in which a component is designed: topological optimization[2] can inspire complex shapes useful to obtain light and stiff structures. With AM "the design drives the shape" concept is valid, opposed to the strategy "the manufacturing drives the shape" which applies with traditional machined parts. Cellular complex structures, called hierarchic structures, may be included in AM components where lightweight, stiffness and high strength to mass ratios are needed. In literature, there are different types of cellular structures like foams (stochastic structures), honeycombs and lattices (periodic

Department of Industrial Engineering (DIN), University of Bologna, Bologna, Italy

Corresponding author:
Antonio Bacciaglia, Department of Industrial Engineering (DIN), University of Bologna, Bologna, Italy.
Email: antonio.bacciaglia2@unibo.it

structures).[3] Lattice structures are composed of simple small elements, such as cylindrical beams, called struts, all together connected to form a unit cell that is repeated hundreds or even thousands of times along the body (Figure 1). The paper[4] includes a complete overview of recent papers on general cell patterns. This unit cell can show different shapes and different topologies, but the easiest structure to be implemented is based on voxels[5] which are cubic unit cell, where eight vertices are linked together following different schemes.[6]

A challenging problem which arises with these structures is the design methodology. On the one hand, even if the advantages of such structures are clear, current design tools available to the engineer, such as CAD (Computer-Aided Design) software packages, still present large limitations: this is mainly because CAD tools use boundary representation technology (B-rep) which is not well suited for lattice structures where the external surfaces are very complex.[7] Some contributions in the literature propose frameworks for lattice generation,[8–10] but the largest part of them developed stand-alone solution not embedded in CAD software. Moreover, the lack of easy interface with Finite Element Method solvers can be noticed. Just to cite an example, the work[11] tries to fill the gap developing an environment embedded in the open-source FreeCad™ software to design different type of 3 D lattices and honeycombs, as commercial CAD tool PTC's CREO does.

A large number of alternative approaches has been developed over the last few decades to describe the design methodology to follow for the generation of 3 D models ready to be manufactured in AM. Following the general workflow, AM machines require the 3 D model of the part to be manufactured be saved in STL or AMF format, so that for manufacturing purposes there is no need for 2 D part drawings. However, 2 D drawings are still necessary to suggest assembly/disassembly sequences, maintenance manual, bill of materials and spare parts nomenclature: in such a framework, the representation of lattice structures could be a challenging task.

The sketching of 3 D parts is the first step of the design workflow in modern CAD systems; in the following, these parts are assembled together, and other parts can be modelled in the assembly if necessary. Finally, 2 D constructive drawings (including GD&T symbols and tooling details) and exploded views are produced in an automatic way to support workshops, manufacturing, maintenance manuals, and illustrated parts catalogues for spare parts. However, the lattice structure representation in 2 D technical drawings hasn't been studied in detail. If the part is modelled with small cell elements (like cylinders, beams, spheres typical of lattice structures), the representation on the drawing becomes hardly understandable because of too small details, and problems of representation can arise. Moreover, an eventual quoting and dimensioning of such a structure could be confusing and operator dependant.

As far as we are concerned, no previous specific researches investigated problems dealing with the representation in 2 D technical drawing of lattice components; neither the ISO drawing standards mention this type of structure, nor specific national standards do. This is the reason why standards Organizations such as International Standard Organization (ISO), ASTM International, American Society of Mechanical Engineers (ASME), Society of Automotive Engineers (SAE), American Welding Society (AWS) should be pressed by companies to develop new Standards dealing with Additive Manufacturing and lattice structures.

This paper highlights some of the problems which should be addressed to propose new representative standards to represent lattice structures, based on the use of conventional symbols to describe shapes and dimensions. The proposed Standard has been preliminarily embedded in a workbench environment in FreeCad™ to test and evaluate it: new commands for this original add-on have been developed in Python language. The framework developed to fill the Standards gap related to this issue can represent lattice structures in 2 D technical documentation using conventional symbols in a simplified way. The proposed methodology allows a conventional representation of lattice structures which is light from a computational point of view but provides all the information required to understand the features of the lattice structures.

This paper is organized as follows: 'Additive manufacturing standards and regulations: State of the art' section describes the available Standards dealing with AM technology and 2 D drawings. Then,

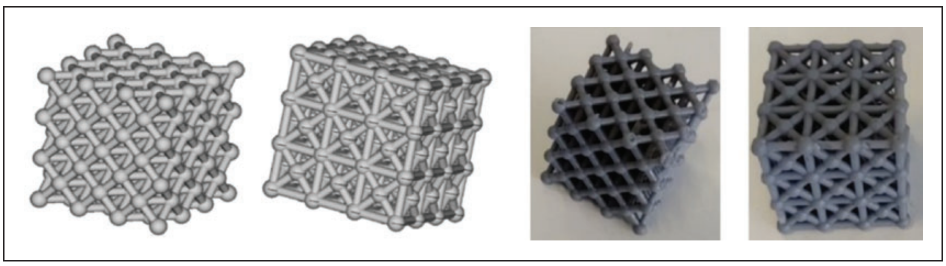


Figure 1. FCC and Octet lattice CAD model in the left and 3 D printed in the right with SLA technique.

lattice structures typical features and discusses the approach which is proposed to represent it in 2D drawings are described. The 'Proposed representative standard' section describes the implementation of the representation methodology in FreeCad^{TM} environment, while the penultimate section shows a case study where the proposed representation methodology is applied. The final section reports conclusions and future works.

Additive manufacturing standards and regulations: State of the art

The Standards are defined as "technical methods, processes, specifications and definitions with respect to a physical system on which there is general agreement as promulgated by recognized standards organizations".[12]

International Standards and regulations are extremely important to facilitate wider adoption of a certain technology, to allow the technical exchange within foreign countries, to guarantee the process consistency and the parameters standardisation and to guarantee an adequate level of safety.

There are several international Standards Organizations and Associations active in different technical fields and technologies. However, focusing the attention on Standards for AM technology, few standards are approved and available to date. This is because the AM technologies are improving rapidly, and no deep knowledge of technologies/materials has been already gained. According to a study made by American National Standards Institute (ANSI),[13] several technology gaps (ANSI identified 93 gaps) can be identified for AM: standards or specifications don't respond adequately to industry needs. Nevertheless, some standards and specifications are already published and the most significant ones are collected in the following, grouped for similar categories.

Terminology. The most important standard (ISO/ASTM52900-15) defines the basic nomenclature, terminology, process definition and commonly used acronyms. Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) have the highest number of standards available due to the widespread use of this kind of technology in aerospace/automotive/medical field.

Standards for PBF and DED. Two standards for PBF process in critical applications are available (AMS7003 from SAE Int. and ASTM F3303-2018 from ASTM Int.) for the production of metal end-user components. A standard guide for DED has been published by ASTM (ASTM F3187-16) and by SAE Int. (AMS7005) to regulate the specific process and the materials.

Metal AM in general, inspections and qualifying training. AWS published a more general standard about the AM for metal components (AWS D20.1/D20.1M:2019) providing processes flowcharts, test builds, performances of machine operators and inspection personnel.

Design for AM. ISO and ASTM published in 2017 general guidelines for the design for AM (ISO/ASTM 52910:2017(E)) and PBF for both metals and polymers (ISO/ASTM 52911-1 and 2:2019(E)). Regarding complex shapes made in AM, such as topologically optimized structures and lattices, ASME published a standard about their dimensioning and tolerances (ASME Y14.46-2017).

Material characterization. ASTM provides important guidelines to characterize properties for metal powders (ASTM F3049-14), while AWS issued guidelines for filler metals, consumables etc. (AWS A5.01M/A5.01:2013).

The application of Standards for the AM technology is very slow and appears as a "vicious loop cycle". On one hand, industries need standards to shift the use of AM parts from prototypes and mock-up models towards critical structural applications. On the other hand, regulatory agencies, such as ASTM, SAE and ISO, need historical data and experience to understand how to deal with these technologies in critical applications in aerospace, automotive and biomedical fields. This stalemate reflects on a slow regulation and certification process, even if Standards will gradually widen their applicability.

Focusing on the AM technology, the high machine/process/material dependency is another important aspect that may slow down its applicability, as mentioned in.[14] For this reason, material and process properties must be accurately checked due to wide changes in final AM parts characteristics: this is true especially in a context where AM requires the respect of existing standards, like the FAR 25 Airworthiness Standard for the Aerospace Industry. In this framework, the U.S. Federal Aviation Administration (FAA) is developing a roadmap for the process qualification and certification for AM applications in aerospace.

Moving to structures drawing Standards, ISO Technical Committee focused recently on drawing standards dealing with rules for parts representation in CAD software, GD&T system (Geometric Design and Tolerancing), roughness indications, isometric 3D representation of components, and composite material representation (EN 4408-001[15])

As a matter of fact, drawing standards (both ISO and ASTM) do not include information about how to deal with the sketching and representation of parts obtained through AM processes. This turns out to be even more problematic because if a complex AM part (lattice structure or topologically optimized component) has to be represented in a 2 D drawing, there are no guidelines about how to deal with it.

Therefore, in this paper, we propose a draft of a Standard for 2 D representation of Bio-inspired lightweight structures such as lattices, being inspired by regulations and standards which have been already published.

2 D drawing importance

From a first perspective, it seems that only 3 D digital models are needed in an Industry 4.0 context[16] to exchange the component design information inside or between companies technical offices: the need for 2 D and assembly drawings seems to be not adequately addressed. However, 2 D drafting can be still used in an industry context where new technologies, such as augmented reality, are used in maintenance operations.[17] This applies as well where 3 D models are exchanged very quickly thanks to universal file formats such as STEP and IGES which are compatible with all the CAD software available nowadays.

2D technical drawings are still used in companies to exchange data between technical office and operators without the need for PC or tablets. Moreover, 2 D drafting can preserve intellectual property better than giving a 3 D model to a customer/third party company by hiding sensitive information and eventually using simplified geometrical representations.

2D drawings are widely used in the maintenance sector, in quoting, and illustrative catalogues. Indeed, Augmented Reality and 3 D manuals require long developing times for animations and this approach makes sense only for high-value maintenance operations.

Moreover, the typical complex geometries that can be manufactured in AM and 3 D printing aren't optimized from a representation point of view by CAD software, and file dimensions of lattice shapes are bulky if compared to 2 D drawings.

In these circumstances, it seems that 2 D technical drawings can still play a role in design and manufacturing. Moreover, since the research community focused on AM is pushing the development of new complex types of structures unconceivable up to a decade ago, it follows that an important gap exists in the representation standards of such complex structures (e.g. bio-inspired ones) in the 2 D technical drafting.

Bio-inspired material structures

There are different types of hierarchic structures that can be used as a constituent material for lightweight component design. Lattice structures are a combination of dense materials and void spaces arranged to create an architectural material with properties not achievable with a single material:[18] this makes these structures very attractive for their lightweight. This important advantage can be exploited in sectors such as aerospace, automotive, transportation industry for lightweight structure employment or as energy absorption structures and finally for anti-sloshing properties (e.g. fuel tanks).

Lattice structures can be classified according to different characteristics which will be summarized in the following, but for further information please refer to Azman et al.[3]

Going deeply with bio-inspired structure classification, a first main distinction can be done based on the periodicity of unit cells; hierarchic structures can be stochastic (foams) or periodic (lattices). For the scope of this paper, only lattice structures will be considered. However, a similar approach to the one discussed in this paper could be developed for foams too. Lattice structures can be subdivided into different categories based on pattern (unit cell type), surface limits, inner progressivity and conformity (Figure 2).

For illustrative purposes, only the lattice structures based on a cubic cell are considered in the following examples, but an extension of this methodology to other kinds of cells can be carried out in a similar way.

A workbench embedded in FreeCad™ called LSWM[11] has been developed at the University of Bologna to investigate and propose a tool for lattice structure design, and it is still in a development phase. Thanks to the experience gained, LSWM has been selected as the software platform where to implement some automation to evaluate the easiness of the representation methodology discussed in this paper: cubic component has been implemented at this stage, but functions to manage other structures are in development.

The six-unit cell topologies (Figure 3) which will be considered in the following of the paper are listed and described below:

- Box: (8 vertices, 12 bars per each cell)
- Body Centred Cubic, BCC (9 vertices, 20 bars)
- Face Centred Cubic, FCC (14 vertices, 36 bars)

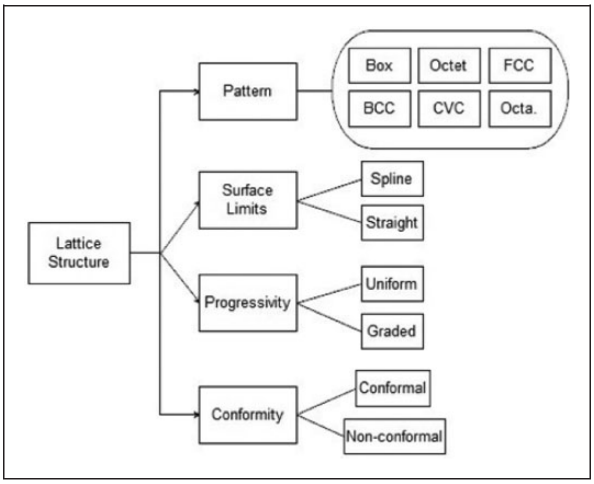


Figure 2. Lattice structure classification (adapted from Azman et al.[3])

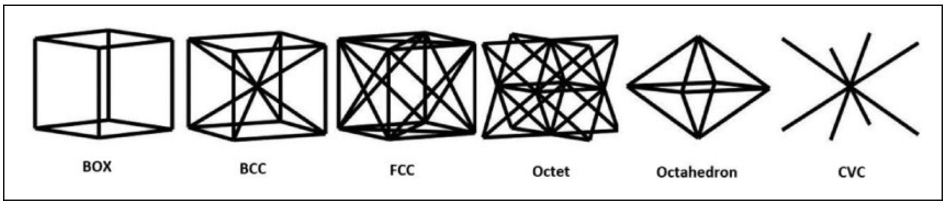


Figure 3. Unit cells library implemented for the scope of this paper.

- Regular octet (14 vertices, 36 bars)
- Octahedron (6 vertices, 12 bars)
- Cube vertex centroid, CVC (9 vertices, 8 bars)

All these kinds of unit cells differ only in the way the eight vertices of a cube are linked together. Cubic unit cells are the simplest and easiest to implement. They can be used as a support for the voxelization method[19] that creates the point cloud needed to generate all the cells. This point cloud is generated in the form of an array of points inside a body at the same distance in all the three dimensions, and then properly connected to create the lattice structure.

Moreover, each line connecting two points, called strut, can be of different types of cross-sections, such as square, circular, triangular and so on. For the scope of this work, only the square and circular shapes will be considered.

Graded lattice structures, whose geometry characteristics change in the structure following a gradient function, are commonly used in industrial applications because the designer can modify the material characteristics in specific limited regions based on the knowledge of applied forces and displacement. In this way optimized and lightweight component can be obtained. The lattice design routines implemented in commercial and research optimization software packages operate by increasing the lattice relative density where the material has to be stiffer. Decreasing the unit cell dimension or increasing the cross-section dimension are the typical strategies followed by software packages.

The conformity is the last property which can be used to characterize lattices. The non-conformal filling is the easiest way to fill a component with hierarchic structures: in this case, the external surface shape is ignored, and the filling operation is based on a fixed unit cell orientation, independent of the body shape. On the other hand, conformal lattice structures are based upon distorted unit cells which follow the external surface curvature and better fit it, trying to obtain more regular meshing.

Proposed representative standard

As introduced in the previous sections, no mention is done in the literature of 2 D drawing Standards for hierarchic structures and lattices that are typically manufactured using AM technologies. It is worth noting that technical 2 D drawings are not necessary for components when AM is selected as manufacturing process: in this case, the 3 D model is usually saved in STL file extension, or in the newest Additive Manufacturing File Format (AMFF), which is under development nowadays.

On the other hand, when designers deal with complex 3 D assemblies, 2 D exploded drawings are necessary for manuals and technical documentation in case of assembly/disassembly and maintenance operations. The assembly drawings are useful to compile in an automatic (or semi-automatic) way the "Bill of Material" (BOM), by labelling each component with a number. This operation is implemented in several of the commercial CAD packages available off-the-shelf and it is widely used in technical departments to obtain the BOM.

The scope of this work is to fill this gap in the availability of Standards for the lattice components representation in 2 D drawings, by spotting the lights on this problem and proposing a draft of a simple and user-friendly representation standard. Literature research has been carried out to find the Standards dealing with problems related to the representation of complex structures in 2 D drawings. The EN 4408-001 regulation about the "Representation of parts made of composite materials" has been detected as a potential source to understand the approach followed by Certification Agencies. In a similar way to what already suggested by the EN 4408-001, a possible way to represent lattice structures in 2 D drawings could be based on simple tables used to summarize the most important lattice structure parameters which describe completely it: they could be positioned over the title block (T/B) section of the drawings.

The following of the paper provides the reader with a description of the tables developed by the authors which can be used to describe in a visual way the features of the lattice structure, according to the lattice dimension characteristics (Figure 4). With reference to Figure 4, d describes the cross-sectional dimension, v the original voxel edge dimension used to fill the component, while L provides with the length of strut elements. To date, only cubic unit cells where $L = v$ have been considered in this research, but in the near future, the developed workbench could handle lattice structures based on parallelepipeds. In this latter case, the unit cell would be based on a cube which is scaled along a direction and L would be different from v. This feature could

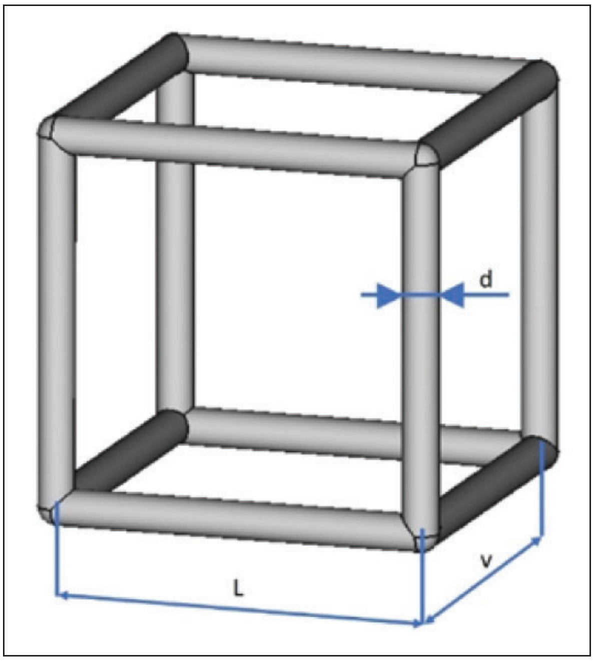


Figure 4. Lattice unit cell fundamental dimensions.

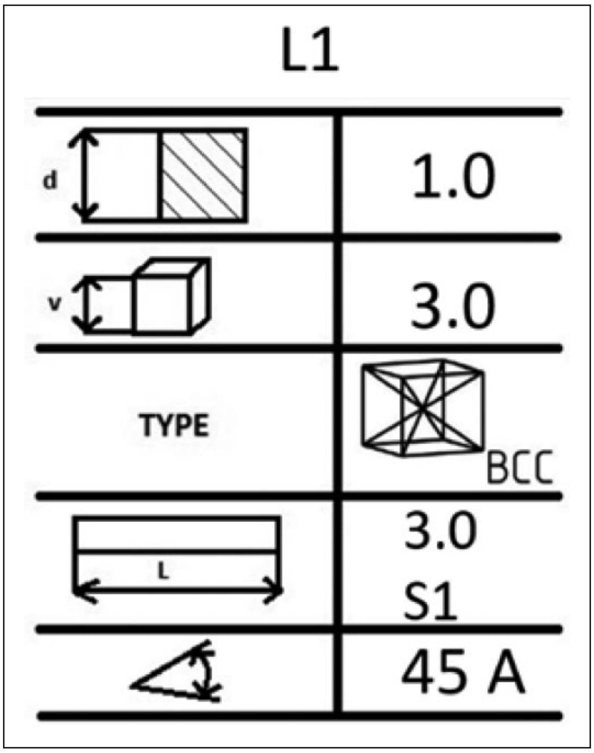


Figure 5. Proposed table to describe uniform non-conformal lattice structures in 2 D drawings.

be kept into account in the tables proposed in this research as well as with the orientation of the scaling transformation.

In the present research, different types of tables have been developed according to the lattice structure they have to refer to.

Uniform non-conformal lattice. The simplest lattice structure is the uniform and non-conformal one, where the unit cells are identical all around the structure and only an infill operation is done when the lattice is created, ignoring the external component surfaces. For this kind of lattice, a particular table is developed (Figure 5).

The first row of the table describes the lattice bar cross-section shape. Two different kinds of symbols can appear according to the cross-section types, i.e. circular (Figure 6(a)) or square (Figure 6(b)). The user must insert the cross-sectional dimension d in millimetres which is automatically listed on the side.

The second characteristic summarized in the table is the cubic edge dimension v (always in millimetres), which is the voxel dimension used for the lattice tessellation: it is represented by the symbols reported in Figure 6(c).

The unit cell type used to fill the component is the property listed in the third row of the proposed table: it is selected from a library available to the designer, as illustrated in Figure 3. An image is added in the third row of the table to show the lattice unit cell type name.

The fourth row of the proposed table describes the strut mean-line length using the symbol included in Figure 6(d). The length L in millimetres is added automatically by the workbench after the user input, right beside the symbol icon. As previously mentioned, with cubic-based lattices L will be equal to v, but in a wider approach where the unit cells are scaled along one (or even two) direction, L could differ. Moreover, an additional label with the indication $S1$ states that a sphere with a radius of 1 mm is added to both the ending points of the strut element: this is carried out to correct the intersecting point of different bars in case of circular cross-section based elements (Figure 7(a)) A similar approach could be carried out with a cube (label with indication $C1$) with an edge of 1 mm added to improve the geometry in case of square cross-section (Figure 7(b)).

The last row provides with information about the orientation of the lattice structure in terms of angles with respect to a datum which can be an axis or a surface identified with a label, in a similar way to what introduced by the GD&T system (according to Figure 5, the lattice structure is oriented with 45° angle with reference to a datum called A). In this specific case, the plane of the lattice elements grid is parallel to the plane of the drawing, and only a rotation of 45° is applied along the axis exiting from the drawing sheet perpendicular to its surface. However, if the lattice pattern is rotated in a freeway along the three axes, all the rotations must be defined in the table to provide the operator with all the information necessary to identify the specific lattice features and reduce possible errors. The order the designer must follow to insert the rotations along the three axes is: z (axis exiting from the drawing sheet), y (vertical axis) and x

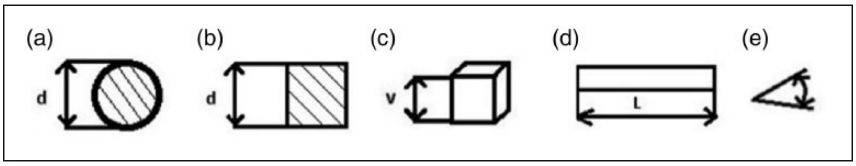


Figure 6. (a) Strut symbols for circular lattice cross-section type; (b) strut symbols for square lattice cross-section type; (c) voxel-based lattice dimension; (d) strut mean line length; (e) lattice reference angle with respect to an axis or a surface.

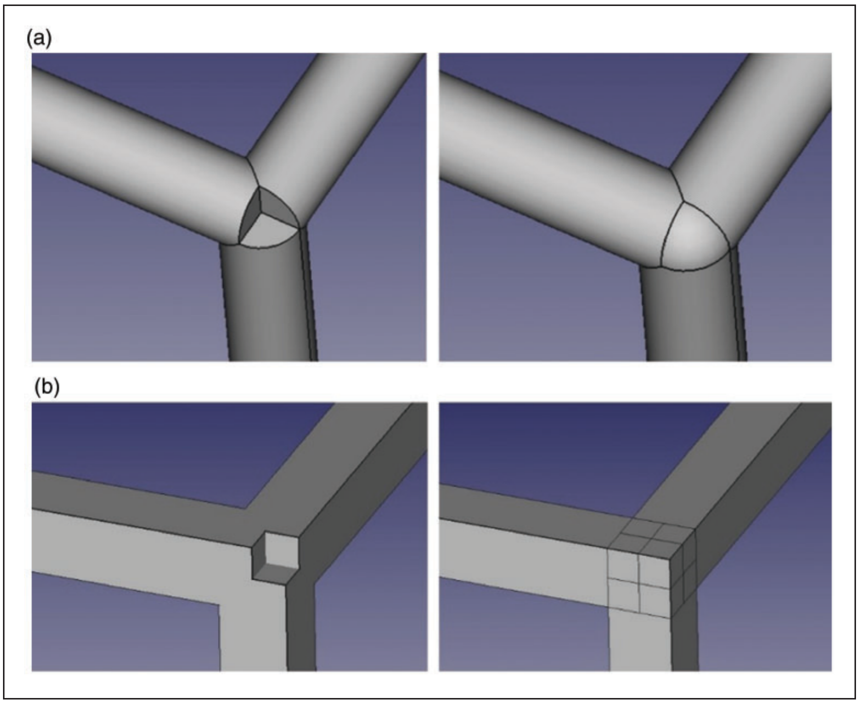


Figure 7. Intersection point of multiple bars needs the placement of: (a) a sphere in case of circular cross-section, (b) a cube in case of square cross-section.

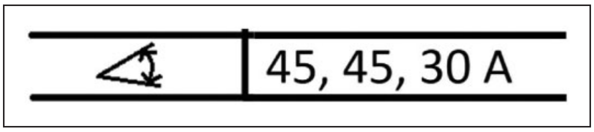


Figure 8. Portion of a table representing a 3 D general orientation of a uniform non-conformal lattice structure.

(horizontal axis). As an example, Figure 8 shows a part of a table for a uniform non-conformal lattice which is oriented in a freeway: 45°, 45° and 30° respectively along axes z, y and x with respect to the datum A which is used to define the horizontal and vertical directions. Clockwise rotations respect to axis directions are considered positive.

Graded lattice structures. A similar table is developed for the graded lattice structures. Additional information, concerning the uniform lattices, are collected in the table to describe the change of lattice properties in space which is a fundamental characteristic in case of graded lattice structures (Figure 9).

Some rows of the table are similar to the ones developed for the uniform lattice, but additional rows contain the change of strut dimension according to a gradient function $d(\mathbf{x})$. In particular, the gradient is centred in a point (H according to Figure 9) whose coordinates are given in the fifth row (the spatial coordinate x goes from 0 to r). The sphere of influence of the gradient will have a radius r whose value is collected in the sixth row and finally, the mathematical expression of the gradient function is given in the last row of the table, where d_f stands for the strut dimension at the centre of the sphere of influence, while d_0 is the general strut dimension. For simplicity, only a linear gradient function has been taken under consideration in this standard proposal. For further details about this kind of structures, the reader is addressed to the source.[20]

Conformal lattice structures. The last type of lattice considered in this project is the conformal one. In this case, the unit cells will be distorted in 2 dimensions to match in the best way an external surface chosen by the designer. A new table is developed and shown in Figure 10.

When compared to the other two tables for conformal lattices, some differences should be noticed:

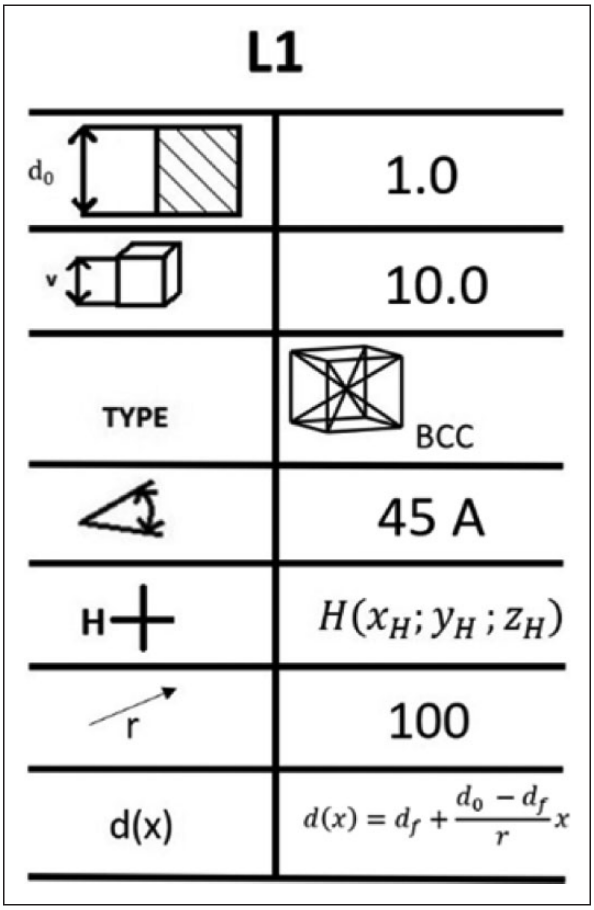


Figure 9. Proposed table to describe graded non-conformal lattice structures in 2 D drawings.

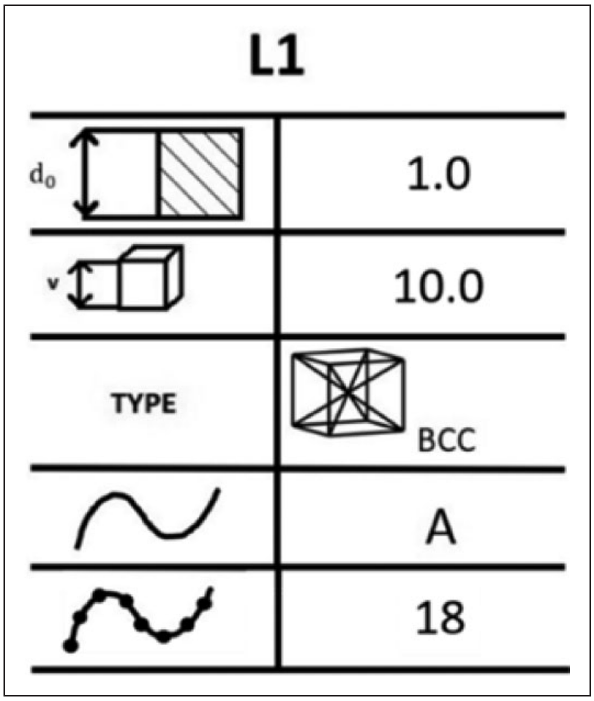


Figure 10. Proposed table to describe conformal lattice structures in 2 D drawings.

the user has to specify the external surface the lattice has to be conformal to with a label. This property is collected in the fourth row. The last row contains the number of subdivisions of the conformal surface which will be equal to the number of lattice cells along that surface. This representation works with constant height components, where the flat side is parallel to the sheet. Conformal structures in two directions could be managed to add a line to define the number of cells in the height direction as well.

A label containing the lattice structure name (i.e. L1 meaning of Lattice number 1) is inserted in the drawing to easily recognize a part filled with periodic structures among all components represented in the technical drawing. This label is used to differentiate several components filled with periodic structure in case of multiple one in the same technical drawing. The same label is taken up over the table corresponding to the specific lattice structure, which contains all the fundamental characteristics.

Moreover, a symbolic image is placed inside the contour of the component filled with a lattice structure according to Table 1, depending on the lattice topology used.

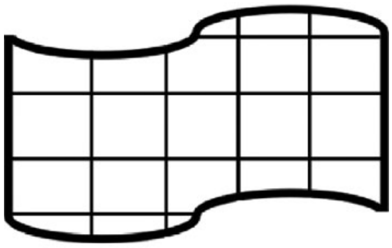
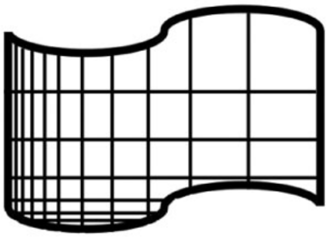
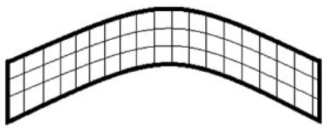
Crosshatches (already used in 2 D drawings for sections) could be used to recognize the components filled with periodic structure in critical tasks such as complex BOM or technical documentation. However, the standards dealing with general principles of presentation for basic conventions for cuts and sections (ISO 128-3:2020) already use crosshatches: the symbols which could be useful to describe a periodic structure are already used to represent insulating materials or electrical windings. Moreover, the introduction of crosshatching would decrease the readability of the technical drawing. These are the reasons why it is preferred to adopt symbols proposed in Table 1 to detect and recognize periodic structures.

Case study

In this section, a simple case study involving a uniform and non-conformal lattice is shown to demonstrate how this proposed representation standard works. The standard symbols and tables automatic generation have been embedded in a FreeCad^{TM} add-on. FreeCad^{TM} is an open-source CAD software based on environments: some are already available, and new ones can be programmed in Python. FreeCad^{TM} automation to draw lattice structures have been already developed[11] and an existent environment is modified to host the lattice structure quoting in technical drafting.

The standard explained in the previous section has been embedded in the *TechDraw* workbench, by coding some macros in Python language to create a user-friendly graphic interface. *TechDraw* is an available FreeCad^{TM} environment which can be used to

Table 1. Collection of symbolic images depending on the lattice structure type, useful to easily detect the lattice structure inside a complex drawing.

Uniform non-conformal lattice structure	
Graded lattice structure	
Conformal lattice structure	

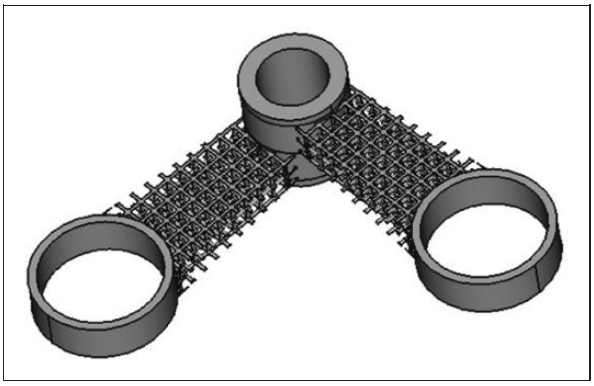


Figure 11. 3 D assembly in FreeCad^{TM} of lattice components.

obtain automatically a technical drawing, being available a 3 D model.

The case study implemented in this paper is based upon an assembly made by 2 rods linked together by a pin, (see Figure 11 for reference). The rods are made of two thin bosses connected by a lattice structure based on a box unit cell.

In the design scenario investigated, the user is tasked to represent the assembly in a 2 D technical drawing. The designer models the 3 D parts in the *Part* and *Part Design* workbenches and assembly it in *Assembly 2* Workbench. When dealing with components filled with lattices, according to the developed standard described in this work, only the fully dense volume has to be modelled, by reducing the computational time and costs for 3 D lattice modelling. Finally, a technical 2 D drawing from the considered assembly is generated automatically thanks to *TechDraw*. In the following, to add the proposed lattice notation in the technical drawing, the user is asked to set the icon shown in Figure 12 (label "1") and follow the instructions. According to the type of lattice involved (label "2" in Figure 12), the designer has to choose the specific strut cross-section shape (label "3" in Figure 12), in the new window that appears in the screen. Finally, the user is asked to insert all the lattice specifications in a new window, such as the lattice component label, the characteristic dimensions and the lattice type among the available ones (label "4" in Figure 12).

By confirming the inputs, FreeCad^{TM} automatically generates the table discussed in Section 4 and places it over the title block (label "5" in Figure 12) obtaining a 2 D technical drawing that is clear and comprehensive.

Thanks to this representative standard, designers can avoid representing the lattice components with small elements (like cylinders, beams, spheres typical of lattice) without making the drawing representation hard to understand because of too small details.

Moreover, thanks to this developed add-on for lattice structures the quoting of such a structure could be clear and far from being operator-dependant.

To better evaluate the advantages, in Figure 12 one of the two lattice rods is represented in the way the CAD software automatically does if the lattice component is imported in the 2 D drawing environment. In this case, all the small details of the structure are represented, while the other picture of Figure 12 is obtained using the proposed standard. It is worth noting that the new standard allows a clearer and more comprehensive drawing, without small undistinguishable details in the component. The representation suggested in this paper can reduce the number of errors that the technicians can do picking components or assembling them. The resulting complete 2 D drawing of the assembly carried out applying the proposed standard can be seen in Figure 13, where the symbolic image of a uniform non-conformal lattice is used, according to Table 1.

Advantages and limitations

The proposal of the methodology discussed in the previous sections aims at filling the gap in the availability of Standards for the representation of periodic structure in 2 D drawings. In this paragraph, a pros and cons analysis of the application of the proposed Standard is discussed based on the experience gained in the simulation of several case studies carried out to test the standard, not included here for brevity.

The proposed standard is intuitive and suits non-expert operators too, thus reducing mistakes in all the

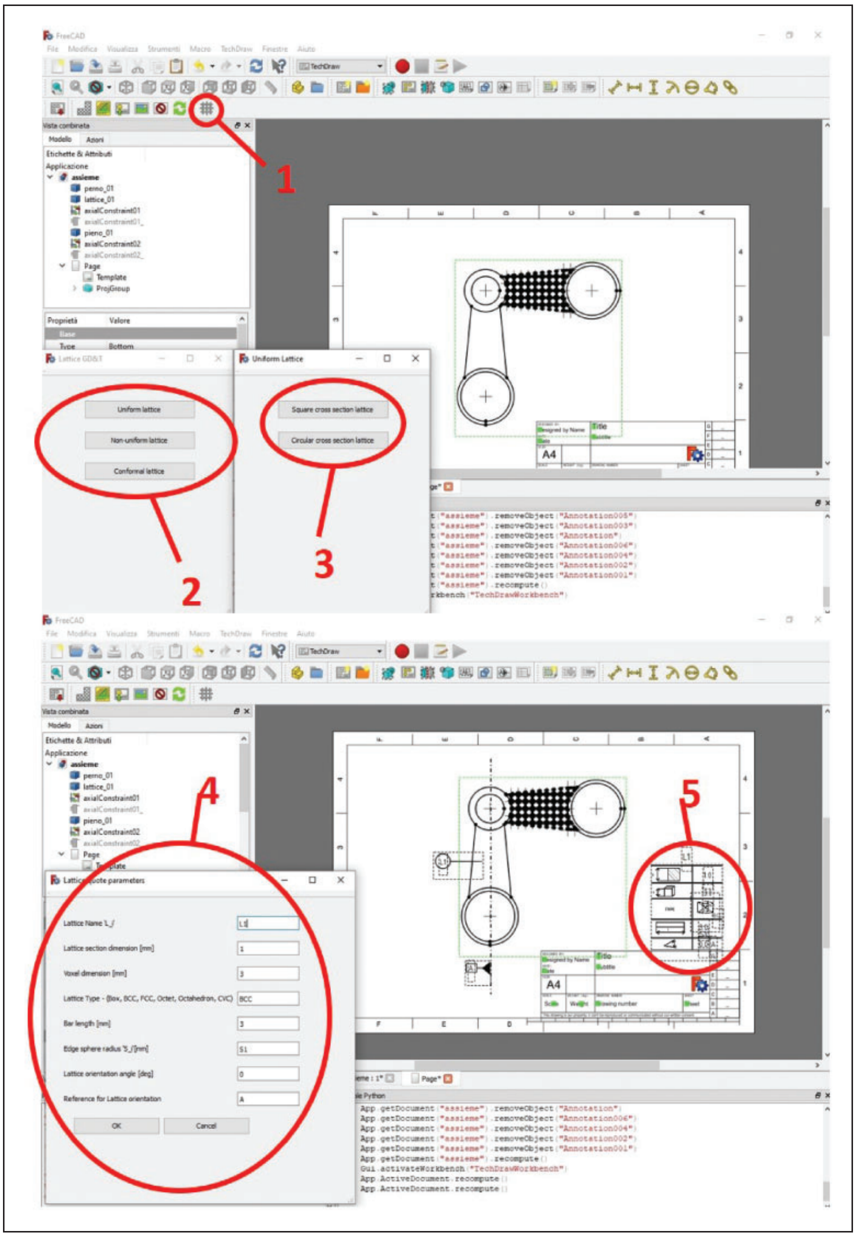


Figure 12. Print screen of TechDraw environment with an additional command (1) for lattice quotes. A new window appears, and the user has to select the right lattice type (2), the cross-sectional shape (3). All the lattice specifications must be declared by the user (4). A new table is automatically created with lattice specifications (5).

scenarios where 2D drawings are still used in the industry. It can handle 3 kinds of lattice structures in a proper way: 1) uniform and non-conformal, 2) graded and non-conformal, 3) uniform and conformal structures. Another advantage of the proposed standard is the introduction of a few symbols in the drawing itself, collecting all the lattice information in tables that do not affect the readability of the technical documentation. This approach imitates what already developed by standardization authorities for composite structures.[14] Moreover, add-ons could be developed to help and guide step by step the designer in the setting of the information needed to characterize the periodic structure. The positioning of tables, datum, and other symbols can be automated developing proper add-ons for specific CAD systems.

On the other hand, some limitations of the Standard suggests the need for further developments. The proposed Standard can handle only voxel-based lattice structures[20] of the strut-and-node arrangement type, while it is still not able to model other kinds of periodic shapes, such as Triply Periodic Minimal Surface (TPMS) structures. A reduced portfolio of unit cell types (Figure 3) and cross-section topologies is noticed in this first embodiment of the Standard and add-on developed for its testing. However, the library developed to test the Standards can be easily populated with new topologies thanks to the open-

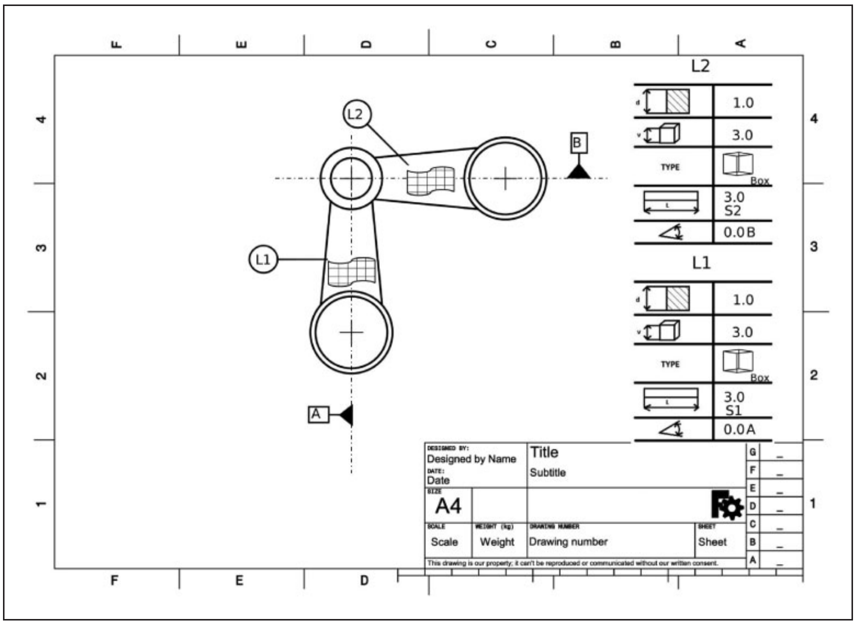


Figure 13. 2 D drawing of the assembly structure made by lattice components using the proposed standard.

source environment of FreeCad^{TM}, or other CAD systems where macro can be implemented. Another problem that may slow down the design process should be highlighted: considering a typical workflow, the designer must model two different parts, namely the 3 D model of the periodic structure, and a fully dense model. The first one is needed for manufacturing purposes (e.g. to obtain the STL file format for AM machines), while the second model is a fully dense representation of the same component. This second model is required by FreeCad^{TM} to obtain the 2 D technical drawing. This is due to the lack of an automated process that recognizes the boundaries of a lattice structure and converts it into a bulk 3 D model: a tool able to carry out this operation could be developed in future works. On the other hand, a hybrid modelling strategy where a dense equivalent part is used in 3 D assembly and the true shape part is modelled apart (it can reach hundreds of MB in case of complex structures) could reduce the computational weight with current computational capabilities: therefore, a 3 D dense model of a part based on complex lattice structures is often available. In the future development of this work, the problem of double representation of the CAD models (dense for 2 D and lattice for manufacturing) will be addressed thanks to the flexibility of CAD macro environments.

Conclusion and future developments

Additive Manufacturing is widening the kind of structures which can be designed in CAD software. AM Standards need to support the drawing of geometrically complex structures to increase the readability of all the technical documents needed during all the design, manufacturing, assembly and maintenance phases of the products lifecycle.

To date, few standards applicable to AM parts have been published, even though AM technologies are spreading and its application is strongly changing the way in which parts are designed and manufactured. For this reason, the standardization authorities should start to chase technological development and introduce more updated standards.

This work aims to discuss the representation of complex structures in CAD systems and to suggest the need for a new representation standard for lattice structures in 2 D technical drawings.

Due to an important gap in the available literature about the specific subject, this paper would like to propose a draft of a new representative standard, based on tables collecting all the important data and characteristics of a lattice component.

This Standard could dramatically decrease the drawing complexity and the number of details which should be included in the drawing and quoted, making the representation clearer and more intuitive for all the insiders.

The lattice component in 2 D assemblies is represented only by the external surfaces, giving to the drawing reader a clear idea of the volume occupied, the position and the constrains with the surrounding components. On the other hand, all the lattice characteristics are summarized in tables. The lattice cross-section type and dimension, unit cell type, voxel dimension, bar length and orientation are listed in a clear way. In this way, the notation is more comprehensive and reduces possible error sources for technicians that have to manufacture and assembly together a large number of components. The standard is flexible enough to allow the introduction of further symbols for the new structures that are under development nowadays and will be adopted by companies in the next years.

In the near future, the environment will be optimized to make the process more automatic and user friendly and the representative standard has to be expanded considering the conformal non-uniform lattices. Additional information should be contained in the proposed table to consider all kinds of gradient function description of the non-uniform lattice.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Antonio Bacciaglia https://orcid.org/0000-0002-4384-6300

References

1. Ian G, Rosen D and Stucker B. *Additive manufacturing technologies*. Boston: Springer, 2015.
2. Sigmund O and Maute K. Topology optimization approaches. *Struct Multidisc Optim* 2013; 48: 1031–1055.
3. Azman AH, Vignat F and Villeneuve F. Design configurations and creation of lattice structures for metallic additive manufacturing. In: *14eme colloque national AIP PRIMECA*, La Plagne, France, 31 March–2 April 2015.
4. Dragoni E and Ciace VA. Mechanical design and modelling of lightweight additively manufactured lattice structures evolved from regular three-dimensional tessellations. *Proc IMechE, Part C: J Mechanical Engineering Science*. Epub ahead of print 7 November 2019. DOI: 10.1177/0954406219885959
5. Bacciaglia A, Ceruti A and Liverani A. A systematic review of voxelization method in additive manufacturing. *Mech Ind J* 2019; 20: 630.
6. Nguyen DS and Vignat F. A method to generate lattice structures for additive manufacturing. In: *2016 IEEE international conference on industrial engineering and engineering management (IEEM)*. Bali, Indonesia, 2016, pp. 966–970.
7. McMillan ML, Jurg M, Leary M, et al. Programmatic generation of computationally efficient lattice structures for additive manufacture. *Rapid Prototyping J* 2017; 23: 486–494.
8. Rosen D. Computer-aided design for additive manufacturing of cellular structures. *Computer-Aided Des Appl* 2007; 4: 585–594.
9. Aremu AO, Brennan-Craddock JPJ, Panesar A, et al. A voxel-based method of constructing and skinning conformal and functionally graded lattice structures suitable for additive manufacturing. *Additive Manuf* 2017; 13: 1–13.
10. Borucinski M and Krolikowki M. Design of non-uniform truss structures for improved part properties. *Adv Manuf Sci Technol* 2013; 37: 77–85.
11. Ceruti A, Ferrari R and Liverani A. Design for additive manufacturing using LSWM: a CAD tool for the modelling of lightweight and lattice structures. In: *SDM 2017: sustainable design and manufacturing 2017*. Cham: Springer, 2017, pp.756–765.
12. www.deloitte.com (accessed 5 August 2020).
13. www.ansi.org/standards_activities/standards_boards_panels/amsc/America-Makes-and-ANSI-AMSC-Overview (accessed 5 August 2020).
14. EASA. Certification Memorandum – additive manufacturing, CM–S-008 Issue 01 issued 04 April 2017.
15. EN 4408-001:2005. *Aerospace series – technical drawings – representation of parts made of composite materials – part 1: general rules*. Brussels: Comite Europeen de Normalisation, 2005.
16. Alcacer V and Cruz-Machado V. Scanning the industry 4.0: a literature review on technologies for manufacturing systems. *Eng Sci Technol* 2019; 22: 899–919.
17. Ceruti A, Marzocca P, Liverani A, et al. Maintenance in aeronautics in an industry 4.0 context: the role of augmented reality and additive manufacturing. *J Comput Des Eng* 2019; 6: 516–526.
18. Park S and Rosen DW. Quantifying effects of material extrusion additive manufacturing process on mechanical properties of lattice structures using as-fabricated voxel modelling. *Additive Manuf* 2016; 12: 265–273.
19. Torigaki T and Fujitani K. Power of a voxel approach to structural analysis and topology-shape optimization in automobile industries. *Japan J Indust Appl Math* 2000; 17: 129–147.
20. Mantovani S, Campo GA and Ferrari A. Additive manufacturing and topology optimization: a design strategy for a steering column mounting bracket considering overhang constraints. *Proc IMechE, Part C: J Mechanical Engineering Science*. Epub ahead of print 15 April 2020. DOI: 10.1177/0954406220917717