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Status, comparison, and future of the representations of additive manufacturing data

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ABSTRACT

An effective representation of additive manufacturing (AM) data is important for ensuring the repeatability of AM processes and the reproducibility of AM parts. Recently, several standardised representations have been developed and used in the industry. While at the same time, a number of other representations have been presented within the academia. The coexistence of different representations generates a series of questions and discussions: What is a representation of AM data? Are the standardised representations comprehensive enough to ensure the repeatability and reproducibility? What challenges have been addressed so far in the presented representations? What are the strengths and weaknesses of each representation? What are the main issues in the field of AM data representation currently? What are the potential research directions of AM data representation in the future? To approach these questions, a review of the existing representations of AM data is presented in this paper. Firstly, an in-depth analysis of the existing representations is provided. Then, detailed comparisons among these representations are made, and a discussion about the main issues in AM data representation is carried out on the basis of the comparisons. Finally, some future research directions of AM data representation are suggested.

1. Introduction

Additive manufacturing (AM), which in the past was also called additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, solid freeform fabrication, freeform fabrication, and 3D printing [1], refers to the technologies used to manufacture 3D objects, in which materials are accumulated layer by layer via specific techniques such as extrusion, sintering, melting, photopolymerisation, jetting, lamination, and deposition [2]. Modern AM technologies firstly emerged with stereolithography in the 1980s and have been applied for prototype production purposes since then [3]. Recently, the developments in computer-aided design (CAD), material processing and forming, equipment recoating, and efficient manufacturing have made the technologies applicable to fabricate end-use products. AM technologies enable manufacturing of products with complex geometries, heterogeneous materials, and customisable material properties. In addition, they also provide good design flexibility, less development time and cost, and fewer waste byproducts, over traditional subtractive manufacturing technologies [4,5]. Convinced by such potential and advantages, some have anticipated that AM technologies would bring revolutionary changes to the industry [6]. Despite the potential and advantages, ensuring the repeatability of AM processes and the reproducibility of AM parts is still considered as one of the biggest challenges to facilitate a broad application of the technologies in the real world industry [7].

In the measurement science roadmap for metal-based AM of NIST [6], repeatability of AM processes and reproducibility of AM parts have been defined, respectively, as the capability to repeat the same AM process (e.g. build-to-build, machine-to-machine, operator-to-operator) and the capability to reproduce the first part up to the *n*th one which should satisfy the design specifications. To address the design validation and conformance requirements of AM parts, Kim et al. [8] extended these definitions with considerations of AM informatics. In their extended definitions, repeatability "incorporates the required data to implement the same procedure over and over with minimum AM process variation", and reproducibility "incorporates the required data to obtain similar results with minimum AM part variation". Based on such definitions, they pointed out that representation and communication of the required data is important for ensuring the repeatability of AM processes and reproducibility of AM parts and for the industry to consistently produce AM products. It is understood that all necessary information that are indispensable for the repeatability of AM processes and reproducibility of AM parts, should be represented and later exchanged in an

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unambiguous and rigorous manner. For the representation of the required data, there are a variety of available ways and a number of challenges. The present paper aims to review the research work and discuss the challenges in AM data representation, and simultaneously shares objectives with AM data exchange via the common underpinnings of AM data representation.

AM data refers to all relevant data captured, used, generated, and exchanged throughout an AM process [9,10]. A representation of AM data is a format, method, standard, or language[1] for representing AM data in a form that can be directly read and interpreted by computer systems [11]. During the past three decades, various representations of AM data have been developed or presented. They can be classified into 3D model representations, 2D slice representations, and integrated representations[2] on the basis of the type of AM data they represent. The major 3D model representations are the stereolithography interface specification (STL) format [12], additive manufacturing file format (AMF) [13], 3D manufacturing format (3MF) [14], Wavefront object (OBJ) format [15], extensible 3D (X3D) format [16], Jupiter tessellation (JT) format [17], rapid prototyping interface (RPI) format [18], surface triangles hinted (STH) format [19], Cubital facet list (CFL) format [20], solid interchange format (SIF) [21], Steiner patch based file (SPF) format [22], polygon (PLY) format [23], standard ACIS text (SAT) format [24], non-manifold boundary representation (B-Rep) method [25,26], feature tree method [27–29], constructive solid geometry (CSG) method [30], voxel method [31–35], and trivariate spline method [36–38]. Representative 2D slice representations are the layer exchange ASCII format (LEAF) [39], stereolithography contour (SLC) format [40], common layer interface (CLI) format [41], Hewlett-Packard graphics language (HP-GL) [42], and multi-material additive manufacturing file (MAMF) format [43]. The main integrated representations include the standard for the exchange of product model data (STEP) [44], coding system method [45], digital thread method [46], integrated data schema method [47], unified storage file format [48], and relational database method [49]. The coexistence of different representations triggers a series of questions: Q1: What is a representation of AM data? Q2: Are the standardised representations comprehensive enough to ensure the repeatability and reproducibility? Q3: What challenges have been addressed so far in the presented representations? Q4: What are the strengths and weaknesses of each representation? Q5: What are the main issues in the field of AM data representation currently? Q6: What are the potential research directions of AM data representation in the future?

This paper attempts to approach these questions via presenting a review of the existing representations of AM data. Even though there are currently a large number of reviews related to AM, only limited number of reviews focuses on AM data representation. To be more specific, representative reviews related to AM are the reviews in [50–120]. Among these reviews, only the reviews presented by Kumar and Dutta [50], Marsan et al. [51], Lipman and McFarlane [52], and Mies et al. [53] are highly related to AM data representation, while other reviews are respectively about a holistic perspective on AM technologies [54–63], a specific AM technology [64–68], AM of a specific material [69–82], an AM process activity [83–91], AM standardisation [92–96], an issue in AM process activities [97–107], computer-aided AM system [108], the application of AM technologies to other domains [109–115], and the impact of AM technologies on other domains [116–120]. Compared to the reviews of Kumar and Dutta, Marsan et al., Lipman and McFarlane, and Mies et al., the review in the present paper is still necessary because: (1) The reviews of Kumar and Dutta [50] and Marsan et al. [51] were made at least two decades ago. They provided an in-depth analysis of representation and transfer requirements for layer manufacturing data and made a qualitative comparison among the different formats of layer manufacturing data at that time. But the reviews only refer to the STL format, the STEP format, and some other formats, and do not include a large number of new representations that have emerged during the past two decades; (2) The review of Lipman and McFarlane [52] proposed an exploration of how the STL, AMF, 3MF, and STEP formats meet the demands of model-based engineering in the context of AM. It provides an introduction and an analysis of these formats and a summary of their features in 3D geometry and tolerance representation. However, the review lacks a detailed comparison of the four formats, an introduction, an analysis, and a comparison of other representations of AM data, and an outlook for the future research on its subject. (3) The review of Mies et al. [53] presented an overview of how AM data was being captured and used to enhance the supply chain and production process, shorten the development times, and improve the reproducibility and quality of parts. Although its focus has certain relevance with AM data representation, it is in nature different from the focus of the review in the present paper.

The rest of the paper is organised as follows. A brief introduction and an in-depth analysis of the existing representations of AM data are provided in Section 2. Section 3 presents a detailed comparison among these representations and carries out a discussion about the main issues in the field of AM data representation. Section 4 ends the paper with a suggestion of some future research directions in AM data representation.

2. Representations of AM data

A review of the existing representations of AM data is started from the first four research questions Q1, Q2, Q3, and Q4. In this section, these questions are approached via a clarification of a representation of AM data and a brief introduction and an in-depth analysis of the existing representations of AM data.

2.1. Clarification of a representation of AM data

In current times, manufacturing data refers to the product and process data used and generated in manufacturing equipment, computer systems, and information systems [121], thus AM data can be naturally considered as the product and process data used and generated in the equipment, computer systems, and information systems for AM. This definition is somewhat abstract. In the literature, a few researchers have provided specific definitions. For example, Kim et al. [7,8] thought that AM data mainly include the part geometry/design data, raw/tessellated data, tessellated 3D model, build file, machine data, fabricated part data, finished part data, and validated part data. Lu et al. [9,47] defined AM data as the data generated, exchanged, and used in the activities of generating AM design, selecting build orientation and support structure, planning process, manufacturing part, post-processing part, and qualifying part. In ISO 17296-4 (2014) [10], AM data is considered as all relevant data captured, used, generated, and exchanged throughout an AM process. In the present paper, AM data is assigned a different specific definition. It covers the AM

[1] In the present paper, the terms format, method, standard, and language share a common meaning in the context of AM data representation. This common meaning is "a way for representing AM data". However, they still have differences in this context. Format is a way that AM data is encoded for storage in a computer file. Method is a particular way for accomplishing AM data representation. Standard is a shared and reusable way for AM data representation that is developed by consensus and approved by a recognised body. Language is a system of symbols and rules for representing AM data.

[2] The term integrated representation in the present paper refers to a representation covering multiple types of data in multiple AM process activities.

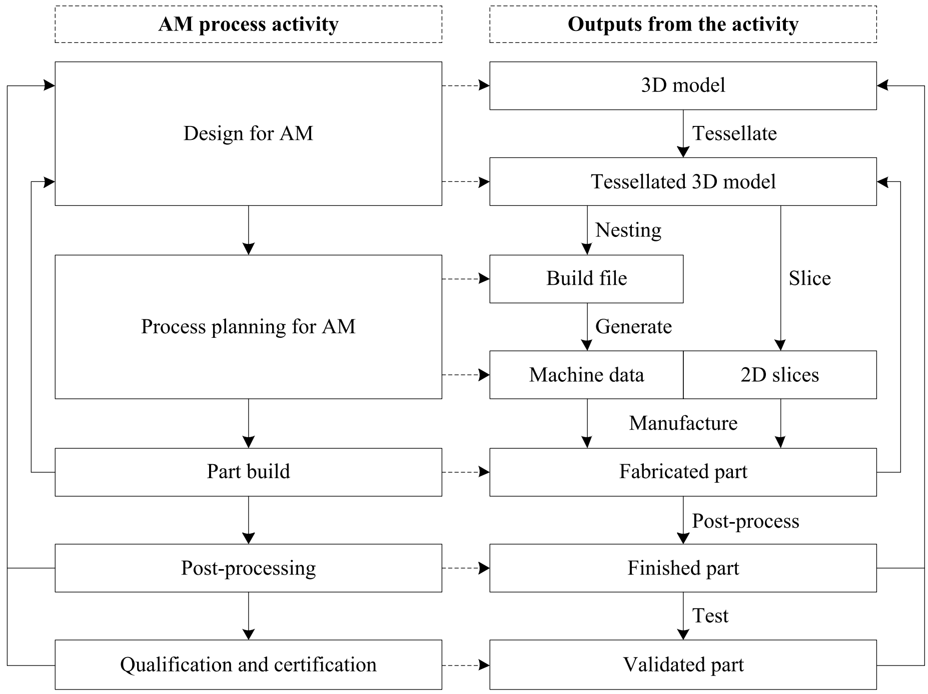

Fig. 1. A general overview of AM process activities.

product data and the nominal process data used to produce AM products.

In general, an AM process mainly includes five activities. They are design for AM, process planning for AM, part build, post-processing, and qualification and certification [2]. A general overview of these activities is depicted in Fig. 1, where each activity will output a specific object after specific operations (e.g. tessellation, selection, slicing) are performed. To achieve the corresponding output, specific data is needed to be the input of the operations for each activity. Kim et al. [8] presented a classification of the input and output data of each of the five activities. They also identified the relationships between each type of the data and the repeatability of AM processes and the reproducibility of AM parts. The details of their classification and identification are shown in Table 1, where each type of the data is of necessity for the repeatability and reproducibility. Therefore, all types of the data should be effectively used and managed. As for the effective management of AM data, Feng et al. [11] pointed out that an essential thing was to develop the representations of AM data.

A representation of AM data is a format, method, standard, or language for representing AM data in a form which can be directly read and interpreted by computer systems [11]. Theoretically, each type of AM data corresponds to a representation or several types of AM data have an identical representation. But until now, only a few types of AM data have been studied in depth and their representations have been developed or presented. These types of AM data are 3D model, 2D slices, and certain types of AM data in part build, post-processing, and qualification and certification. Tables 2, 3, and 4 respectively list the existing major 3D model, 2D slice, and integrated representations. In the following three subsections, a brief introduction and an in-depth analysis of each representation will be provided, respectively.

2.2. 3D Model representations

2.2.1. STL format

The STL format [12] is a file format (.stl) used to represent the 3D model data for AM. It was developed by 3D Systems in 1987 and has remained the same for three decades. The STL format is the most used representation of 3D model data and has become the de facto standard representation in the AM industry, though it has not been officially standardised to date [122]. So far, almost all commercial CAD systems have provided the support of the import and export of a STL file and almost all AM machine manufacturers have included the support of STL file format in their products.

The STL format represents geometry via a simple approximation technique called tessellation, a process of covering a surface with one or more geometric shapes (e.g. triangles, polygons) which have no overlaps or gaps [122]. To represent a 3D model for AM, firstly standard surface triangulation algorithms are used to triangulate the surface of the model. The surface is then covered by a list of planar triangular facets (i.e. planar triangles). After that, the geometry of the 3D model is encoded through the three unique vertices and one normal of each planar triangle. Finally, an ASCII (American Standard Code for Information Interchange) or a binary STL file that describes the geometric data of the 3D model is generated via storing the encoded geometry in ASCII or binary codes. Among the two types of STL files, the ASCII STL file is human readable and takes up more storage space. It is usually used for debugging and testing. Conversely, the binary STL file is generally used for storage, as it is not easy to read and needs less storage space than the ASCII one for the same 3D model [50,51].

As can be seen from the above description, the biggest advantage of the STL format is that it is very simple, as it only requires the standard surface triangulation algorithms, which are known to be simple, accurate, and robust compared to other approximation algorithms, to convert a 3D model to its STL format. In addition, the format has advantages in the aspects of wide range of input, enabling the STL file to play the roles of representation, storage, and exchange formats and good processing capability for STL file splitting issue [50,51].

Though the STL format has obvious advantages in several aspects, its shortcomings are also not to be underestimated. According to the summaries of Kumar and Dutta [50], Marsan et al. [51], and Chakravorty [122], the format has the following shortcomings: (1) It represents a lot of redundant data. (2) The accuracy of

Table 1
The data related to AM process and the relationships between each category of the data and the repeatability of AM processes and the reproducibility of AM parts. Notes: Geometry, GD&T, surface roughness, materials, colours, texture, and tessellated geometry are commonly referred to as 3D model data. Process consistency data refers to the data for characterising the consistency of AM process, such as laser beam power, wavelength, and mode, inert gas or air rate and ratio, pressure and air temperature of a chamber, humidity control, and layer thickness. Surface texture improvement related data refers to processes for achieving designated surface structures and properties, such as shot peening, painting, and hardening, and their implementation details.
Source: This table is created based on reference [8].

AM process activity	Relevant data	Repeatability	Reproducibility
Design for AM	Geometry	■	■
	Geometric dimensioning and tolerancing (GD&T)	■	■
	Surface roughness	■	■
	Materials	■	■
	Colours	■	■
	Texture	■	■
	Tessellated geometry	■	■
	Design requirements		■
Process planning for AM	Build orientation	■	■
	Support structure	■	■
	2D slices	■	■
	Process setup plans	■	■
	Process parameters	■	■
Part build	Machine setup parameters	■	■
	Material characteristics	■	■
	Process consistency	■	■
	Motion or position accuracy	■	■
Post-processing	Support removal related data		■
	Property enhancement related data		■
	Accuracy enhancement related data		■
	Surface texture improvement related data		■
Qualification and certification	GD&T testing related data		■
	Defect testing related data		■
	Microstructure testing related data		■
	Surface roughness testing related data		■
	Part property testing related data		■

Table 2
The major 3D model representations in the literature. Note: NMBR stands for non-manifold B-Rep.

Representation	Relevant institution, standard or scholars	Filename extension	References
STL format	3D Systems, Inc. (1988)	.stl	[12]
AMF format	ISO/ASTM 52915 (2016)	.amf	[13]
3MF format	Microsoft Corp. & 3MF Consortium (2018)	.3mf	[14]
OBJ format	Wavefront Technologies, Inc. (1995)	.obj	[15]
X3D format	ISO/IEC 19775-1 (2013)	.x3d/.x3dv/.wrl	[16]
JT format	ISO 14306 (2017)	.jt	[17]
RPI format	Rock and Wozny (1991)	.rpi	[18]
STH format	Brock Rooney & Associates, Inc.(1991)	.sth	[19]
CFL format	Cubital, Ltd. (1994)	.cfl	[20]
SIF format	McMains (2000)	.sif	[21]
SPF format	Paul and Anand (2015)	–	[22]
PLY format	Turk G (1994)	.ply	[23]
SAT format	Spatial Technology, Inc.(1996)	.sat	[24]
NMBR method	Kumar and Dutta (1997; 1998)	–	[25,26]
Feature tree method	Kou and Tan (2005; 2006); Kou et al. (2006)	–	[27–29]
CSG method	Panhalkar et al. (2013)	–	[30]
Voxel method	Chandru et al. (1995); Hiller and Lipson (2009); Doubrovski et al. (2015); Aremu et al. (2017); Bader et al. (2018)	–	[31–35]
Trivariate spline method	Massarwi and Elber (2016); Ezair et al. (2017); Dokken et al. (2018)	–	[36–38]

Table 3
The major 2D slice representations in the literature.

Representation	Relevant scholars or institution	Filename extension	Reference
LEAF format	Dolenc and Malela (1992)	.leaf	[39]
SLC format	3D Systems (1994)	.slc	[40]
CLI format	Commission of the European Communities (1994)	.cli	[41]
HP-GL language	Hewlett-Packard (1997)	.hpgl	[42]
MAMF format	Zhang and Joshi (2017)	–	[43]

the approximation and the efficiency of the conversion contradict with each other. (3) It is incapable of representing colour, materials, and texture. (4) Truncation errors, inconsistent normals,

Table 4
The major integrated representations in the literature.

Representation	Relevant standard or scholars	Filename extension	Reference
STEP standards	ISO 10303-1 (1994)	.stp/.step	[44]
Coding system method	Ingole et al. (2008)	–	[45]
Digital thread method	Nassar and Reutzel (2013)	.xml	[46]
Integrated data schema method	Lu et al. (2015)	.xml	[47]
Unified storage file format	Baumann et al. (2016)	–	[48]
Relational database method	Prater (2017)	–	[49]

incorrect intersections, and facet degeneracy will arise in the conversion. (5) It does not provide a checking mechanism for watertight geometry. (6) The repair of an STL file with incorrect information is time-consuming and error-prone. (7) An STL file lacks the description of topological, process related, and auxiliary information. (8) The units (e.g. mm, inch) used in the 3D model cannot be specified in an STL file.

To overcome the shortcomings of the STL format, a number of scholars and institutions presented their solutions. These solutions are either based on the idea of improving the method or built upon the idea of replacing it. For the improvement of the STL format, Leong et al. [123] proposed a generic solution to address the issue of missing facets in the proper creation of a prototype; Stroud and Xirouchakis [124] presented an extended version of STL format with the advantages of avoidance of volume distortion for consistent control of slice and layer approximations and allowance of the attachment of manufacturing information; Chiu and Tan [125] proposed a revised version of STL format to represent multiple material objects in CAD systems; Wu and Cheung [126] presented a scheme to enhance the approximation accuracy and extend the functions of the STL format; Pan and Zhou [127] designed an effective filtering and optimisation algorithm for the STL format; Lee and Kim [128] proposed a method to generate a deformed model which satisfies the given error criteria from an STL model; Yin [129] developed an extended STL file format with the strengths of reducing the time and error in modelling process and improving the storage capability; Navangul et al. [130] presented a chordal error based approach to locally reduce the CAD to STL translation error; Zha and Anand [131] designed a surface-based modification algorithm to adaptively and locally increase the facet density of a STL model; Manmadhachary et al. [132] presented an approach to improve the accuracy, surface smoothing, and material adaption in STL files; Hiller and Lipson [133] developed a new compact extensible markup language (XML) based AM file format named as STL 2.0, which is actually the prototype of the AMF format jointly developed by the International Standardisation Organisation (ISO) and the American Society for Testing and Materials (ASTM) [13].

For the replacement of the STL format, some scholars and institutions either developed new representations or introduced existing representations from other fields to 3D model data representation for AM. The developed representations are the AMF format [13], 3MF format [14], OBJ format [15], X3D format [16], JT format [17], RPI format [18], STH format [19], CFL format [20], SIF format [21], and SPF format [22]. The introduced representations mainly include the PLY format [23], SAT format [24], non-manifold B-Rep method [25,26], feature tree method [27–29], CSG method [30], voxel method [[31–35], and trivariate spline method [36–38]. A brief introduction and a specific analysis of each of these representations will be respectively provided in the following subsections.

2.2.2. AMF format

The AMF format [13] is a file format (.amf) used to represent the 3D model data for AM. It was introduced in 2009 as a complete replacement of the STL format and was dubbed the STL 2.0 format at that time. In 2013, the so-called STL 2.0 format was officially named as AMF format and the first version was published by ISO and ASTM, i.e. ISO/ASTM 52915 (2013) [134]. This standard was later revised and was published in 2016. The latest AMF format provides the support of representing the geometry, materials, colour, texture, constellations, and metadata of a 3D model. It is superior to the STL format at all technical aspects. But unfortunately, the format has not yet been widely adopted by the AM industry. Only a few AM related companies, such as Dassault Systèmes, Autodesk, and Stratasys, have included it in their products. The reason can be roughly explained from two aspects. On the one hand, ISO and ASTM, the developers of the AMF format, lack comprehensive consultation with the key players in the AM industry before turning it into an official standard format [122]. On the other hand, in addition to the AMF format, there are other alternative methods, such as the 3MF format [14], the OBJ format [15], and the X3D format [16], where the 3MF format is the most representative one. This format also aims to be an alternative to the STL format and it will be explained in details in the next subsection. Now look at the AMF format a little more deeply.

The AMF format addresses the issues of the STL format via using an XML format [135] with a hierarchy of six fundamental elements, i.e. geometry, materials, colour, texture, constellations, and metadata. Like the STL format, this format also uses triangular meshes to describe the surface of a 3D model. However, the AMF format allows the use of curved triangles to describe curved surfaces. By this way, a curved surface can be covered without using a large number of triangular facets, which overcomes the deficiency of the STL format with respect to the aspect of mutually contradictory approximation accuracy and conversion efficiency. In addition, the AMF format offers support for various modern requirements of AM, such as graded colours, mixed and graded materials, microstructures, and pores [122]. The constellation element of the format allows users to specify the location and orientation of multiple objects. In the AMF format, users can specify the scale in different units and can add additional information about the objects (e.g. name, authorship, volume). Last but not the least, the AMF format is technology independent, easy to implement and understand, scalable, efficient, and both backwards and future compatible [13].

It is without doubt that the AMF format is better suitable for modern AM industry than the STL format. However, there is still room for improvement. According to the studies of Yu et al. [136] and Paul and Anand [22], the AMF format mainly has two inadequacies: (1) The formulation in the format brings the issues of inconsistent normals and undefined end-tangents. (2) The slicing process taking an AMF file as input may lead to the same approximation error as in the STL format. To further improve the format, Yu et al. [136] proposed a new formulation based on triangular Bézier patch which is capable to address the issues caused by inconsistent normals, ambiguous tangents, and recursive dense mesh generation; Paul and Anand [22] presented a new file format called SPF format which uses curved Steiner patches instead of planar triangles for not only approximating the surfaces but also generating the slices.

2.2.3. 3MF format

The 3MF format [14] is a file format (.3mf) used to represent the 3D model data for AM. It has been developed by Microsoft internally (alongside the development of Windows 8 and 10) for a few years before 2015. In 2015, Microsoft announced the establishment of 3MF Consortium, an industry consortium working to study the further development and improvement of the 3MF format. They included a number of AM related companies as the founding members of the consortium. Under the joint efforts of the members, over fifteen AM related companies have so far implemented the 3MF format in their products [137].

Similar to the AMF format, the 3MF format is also XML-based and also features geometry representation via triangular meshes. However, the format does not allow the use of curved triangles in geometry representation and can generate a more compact and size-friendly file than the AMF format. A 3MF file consists of a description of a 3D payload, which includes the required part 3D model and the optional parts core properties, digital signatures, print ticket (i.e. AM settings), thumbnail images, 3D texture, and metadata [14]. The 3MF format is also capable of encoding the colour, materials, and texture of a 3D model. In addition, as described by the 3MF Consortium, the 3MF format also has the following advantages [138]: (1) Complete: A 3MF file can provide a description of all of the necessary 3D model, material, and property data. (2) Human readable: The common structures like OPC, ZIP, and XML can be used in the format to ease development. (3) Simple: The format has a short and clear specification, which makes development easy and verification fast. (4) Extensible: The XML namespaces used in the format allow extensions under the premise of ensuring compatibility. (5) Unambiguous: The format provides clear language and consistency tests to ensure the consistency of a 3MF file from digital to physical. (6) Free: The access and implementation of the format are free of royalties, patents, and licensing.

The 3MF format is still in its infancy and thus has not yet enjoyed wider adoption than the STL format. Since a number of AM related companies have participated in the 3MF Consortium and included the format in their products, adoption seems to be just a matter of time [122]. Leaving aside the adoption issue, the approximation accuracy issue still exists in the format since curved triangles are not allowed to be used. Even though the format can use more planar triangles than the STL format to approximate a curved surface to further reduce the approximation error since it has well solved the file size issue, the approximation accuracy issue has not been fundamentally addressed. Last but not the least, there is a big doubt among 3MF users: How free access and implementation of the format will be?

2.2.4. OBJ format

The OBJ format [15] is a file format (.obj) used to exchange 3D graphics between heterogeneous 3D graphics systems. It was firstly developed by Wavefront Technologies and then adopted by other 3D graphics system vendors due to its open source license and simplicity. The format was introduced to the representation of 3D model data for AM by some AM communities as it can well satisfy the requirement of manufacturing in multiple colours and materials. Currently, the OBJ method has become the second most used representation of 3D model data in the AM industry [122].

The OBJ format can represent geometry via tessellations with polygons, free-form curves, or free-form surfaces. It also supports both ASCII and binary encodings of a generated file, and a trade-off between the approximation accuracy and the file size has to be sought if tessellations with polygons are utilised. When tessellating with free-form curves or free-form surfaces, a curved geometry will be faithfully encoded without losing any data and sacrificing file size, which makes it possible to leverage the method in high precision AM. The format allows users to store the colour and texture data in a separate file, which is called a material template library (MTL) file [139]. An OBJ file accompanied by a MTL file is capable of rendering a multicolour textured model. Besides, the format also allows the use of a more convenient way called texture mapping to specify the colours and textures of a 3D model.

From the perspective of 3D model data representation for AM, the biggest drawback of the OBJ format is that it is more complicated than the STL format. Because of this, repairing an OBJ file is much more troublesome than repairing an STL file. Also, there are not many available tools for editing an OBJ file. Another drawback of the format derives from the use of the paired MTL file with each OBJ file. When dealing with a large number of paired MTL and OBJ files, it is easy to lose the pairing information, which may result a rather chaotic situation [122].

2.2.5. X3D format

The X3D format [16] is a file format used to represent, storage, retrieval, playback, and communicate 3D scenes and objects. It was developed as the successor of the virtual reality modelling language (VRML) [140] (a representation of 3D interactive vector graphics developed particularly with the World Wide Web) in 2001 and was published as an ISO standard in 2004 (ISO/IEC 19775-1 (2004) [141]). So far, the standard has been revised twice and its latest version is ISO/IEC 19775-1 (2013) [16]. The format has a rich set of modularised features that can be tailored to use for various purposes [142]. During the past two decades, the X3D (VRML) format has been introduced into the field of AM to represent the 3D model data [133].

The X3D format can encode surface geometry in an XML format (.x3d) [143], a classic VRML format (.x3dv) [144], or a compressed binary format (.wrl) [145] via polygonal meshes or non-uniform rational basis splines (NURBS). It can also be leveraged to represent the appearance related data like colour, texture, and transparency. However, a number of constructs in the format, such as animations, lights, sounds, and hyperlinks, are meaningless for AM data representation. In addition, the format has no provision for describing multiple materials or arbitrary microstructure [133].

2.2.6. JT format

The JT format [17] is a file format (.jt) used to visualise, integrate, archive, and transfer the 3D geometric data and product manufacturing data derived from CAD systems. It was originally developed by Engineering Animation and Hewlett Packard and was implemented as a long term data archival method by Siemens in 2007 [146]. The format was officially published as an ISO standard for 3D visualisation in 2012 (ISO 14306 (2012) [147]), and was updated in 2017 [17]. Recently, a few scholars including Christ et al. [148], Arnold et al. [149], and Grimm et al. [150,151] introduced and applied the format to AM data representation.

The JT format can describe 3D geometry via tessellations with any combination of triangulated facets and B-Rep surfaces. It can also encode the visual attributes (e.g. textures, materials), product and manufacturing information (e.g. dimensions, tolerances), configuration, and other types of metadata either exported from a CAD system or imported to a product data management system. In addition, another important feature is that the format is capable to store the data in a lightweight file (just 10% of the size of a native CAD file in general), which makes it ideal for Internet collaboration. Due to these characteristics, the JT format was seen as a promising representation of globally distributed AM data [151]. Nonetheless, this format has not yet been widely used in the AM industry. The major reason can be roughly explained as follows: The JT format is too complicated for AM data representation. It includes some higher order representations like NURBS and other types of B-Rep surfaces, which are not really necessary for AM applications. Furthermore, the specification of JT is more convoluted than the specifications of AMF and 3MF. It is not so easy to write consistent parsers to edit, import, and export a JT file.

2.2.7. RPI format

The RPI format [18] is a file format (.rpi) that can be used to represent the 3D model data for AM. It was developed for solid freeform fabrication by Rock and Wozny. In this format, a 3D model is described by a vertex list and a facet list, where the vertex list consists of a list of all vertices of the 3D model and the indices of these vertices, and the facet list refers the vertices through their indices. The RPI format supports the representation of facets models, CSG primitive models, and CSG based solids. It can also store all related topological and process data [50].

2.2.8. STH format

The STH format [19] is a file format (.sth) that can be used to represent the 3D model data for AM. It was developed for rapid prototyping by Brock Rooney & Associates. The format also uses triangulated B-Rep. But unlike the STL format, the STH format requires less storage capability and allows the application of more efficient slicing algorithms because it can efficiently store vertex and connection data with flexible rules [51].

2.2.9. CFL format

The CFL format [20] is a file format (.cfl) that can be used to represent the 3D model data for AM. It was developed to overcome some shortcomings of the STL format by Cubital. In this format, a 3D model is represented by a list of polygonal facets (i.e. planar polygons) which may have multiple holes. The coordinates of the vertices of each facet are stored and indexed to describe this facet. The storage space can be saved and the connections between facets can be captured by this way. The CFL format allows the description of a 3D model as a list of 2D sliced contours and support the representation of topological data [51].

2.2.10. SIF format

The SIF format [21] is a file format (.sif) that can be used to represent the 3D model data for AM. It was developed for layered manufacturing data exchange by McMains. Similar to the CFL format, this data format is also based on B-Rep and also represents a 3D model by a set of planar facets, where each facet is described via the position of all its vertices in 3D space. But differently, the SIF format offers constructs for efficient representation of cylinders and spheres and allows a user to specify the anticipative maximum error.

2.2.11. SPF format

The SPF format [22] is a file format that can be used to represent the 3D model data for AM. It was developed to solve the approximation accuracy issue of the AMF format by Paul and Anand. As explained in the description of the AMF format, the slicing process of an AMF model may lead to the same approximation error as in the STL format since the curved triangles are needed to be recursively sub-divided to planar triangles in this process. To address this issue, the SPF format uses curved Steiner patches for approximating the surfaces and generating the slices. Therefore, this format can significantly reduce the chordal and profile errors in the AMF format.

2.2.12. PLY format

The PLY format [23] is a file format (.ply) which was principally developed to store and view data from 3D scanners by Turk. It was suggested to be used for the representation of 3D model data for AM by some AM communities [133]. This format uses polygon meshes to describe a 3D model. It can be used to encode the colour and texture information.

2.2.13. SAT format

The SAT format [24] is a file format (.sat) commonly used to save modelling information by the ACIS geometric modelling kernel. It was developed for manufacturing data exchange by Spatial Technology. This format is based on B-Rep and can be used to quickly rebuild the topological data structure of a 3D model since it is centred on the internal topological data structure of ACIS [152]. However, because of this approach, the format is difficult to understand and unsuitable for AM data exchange [133].

2.2.14. Non-manifold B-Rep method

To represent the geometric, topological, and material information of heterogeneous objects, Kumar and Dutta [25,26] presented a non-manifold B-Rep based method. In this method, the material information of a heterogeneous object is firstly captured by modelling its composition. Then a new mathematical model is established to model them. By leveraging a non-manifold B-Rep scheme to implement the mathematical model, the computerised representation of the heterogeneous object can be achieved. The presented method can be easily adapted into most of the existing solid modelling systems because it is based on a similar scheme of these systems. However, it just focuses on modelling and representing the composition of materials and does not take into account the description of their microstructure.

2.2.15. Feature tree method

To satisfy the requirement of representing the material distributions of a heterogeneous object for layered manufacturing, Kou and Tan [27,28] designed a novel data structure named heterogeneous feature tree. In a heterogeneous feature tree, the material variation dependency relationships are hierarchically organised, which makes it intuitive to model the design intent and different types of material gradations. To address the strong data redundancy and low data consistency issues of the heterogeneous object representation methods based on manifold B-Rep, Kou et al. [29] proposed a method to describe the complex heterogeneous objects having geometry intricacies and complex material distributions. This method respectively uses non-manifold heterogeneous cells and heterogeneous feature trees to represent the geometry and material distributions. Compared to the manifold B-Rep methods, the proposed method can obtain heterogeneous object models with higher data consistency and lower data redundancy and avoid unnecessary and repetitive computations. But it is more complicated in terms of both data structure and algorithm.

2.2.16. CSG Method

CSG was originally a solid modelling technique allowing a solid modeller to use the Boolean combination of simple objects to create a complex object. It was introduced into AM data representation as the basis of a format for printed electronics by Panhalkar et al. [30] since there is currently a lack of a standard representation which can be used to produce electronic components in layers. This format supports the representation of both the 3D model in the form of CSG primitives and Boolean operations and the manufacturing data related to AM based printed electronic process. It can also be used to create layers automatically by slicing algorithms.

2.2.17. Voxel method

Voxel is the abbreviation of volume pixel. It is a unit of graphic information which defines a point in 3D space. Voxel-based modelling is the use of a collection of voxels to model 3D objects. Compared to traditional solid modelling techniques (e.g. B-Rep, CSG, feature-based modelling), voxel-based modelling has several advantages, such as offers simple, intuitive, unambiguous, and unique representation, has identical complexity for all objects, and easily incorporates heterogeneity and anisotropy of models into analysis [153]. Due to the advantages, voxel-based modelling was introduced into the field of layered manufacturing and a voxel-based method to geometric modelling for layered manufacturing technologies was proposed by Chandru et al. [31]. In this method, a set of layered manufacturing related issues, such as determining layer thickness, generating slices, and estimating surface properties, was studied, and a geometric workbench for rapid prototyping based on the method was outlined. Benefiting from the advantages of voxel-based modelling, the proposed method would be close to ideal for exploiting new layered manufacturing technologies. However, since it is based on voxels and slices, designers have to think in terms of voxels and slices when using it. In addition, the boundaries of a 3D model require additional computation in the method and true parametric surfaces cannot be modelled by the method [50].

Though voxel-based modelling has several shortcomings for AM, a few researchers continued to study its application in AM. For example, Hiller and Lipson [32] studied the use of pre-existing physical voxels as a material building-block for AM and presented the theoretical underpinnings for a new massively parallel AM process in which 3D matter is digital. Doubrovski et al. [33] leveraged the voxel-based fabrication technique via material property mapping and presented a method for form generation combined with material property allocation. Aremu et al. [34] presented a computationally efficient, voxel-based method to construct and skin the conformal and functionally graded lattice structures for AM. Bader et al. [35] presented a multi-material voxel-based method for AM in which the physical visualisation of data sets can be commonly associated with scientific imaging.

2.2.18. Trivariate spline method

In mathematics, a trivariate spline is a function defined piecewise via three-variable polynomials. Trivariate spline based modelling is the use of trivariate splines to model 3D objects. It has several advantages over voxel-based modelling [154]: (1) This technique decouples geometric modelling from attribute modelling, in which complex geometries with simple attributes or simple geometries with complex attributes can be modelled at the resolution that is the most suitable for them; (2) Trivariate spline representations can greatly save storage space and execution time; (3) Trivariate splines, especially trivariate NURBSs, are terse representations that can model a signal with moderate noise; (4) Trivariate splines generally model a smooth function with fewer points. Because of these advantages, a few researchers introduced the technique into the representation of 3D geometry for AM.

Massarwi and Elber [36] proposed a volumetric representation for geometric modelling that is based on trimmed trivariate B-splines. This representation includes various volumetric models, each of which can be decomposed into and defined by a complex of volumetric cells. Each cell can represent a variety of additional varying fields over it and the entire model. Due to these capabilities, the representation is capable to represent and manage heterogeneous materials for AM. On the basis of the representation of Massarwi and Elber, Ezair et al. [37] presented an efficient method that enables the direct slicing and manufacture of functionally graded material objects using AM. They also demonstrated that the method is flexible, since it allows the application of any material function to the volume of a 3D model. Dokken et al. [38] studied and compared the trivariate hierarchical B-splines, T-splines, and LR B-splines for representing 3D model in CAD and AM. Through the study and comparison, they found that the trivariate spline representations can address the tolerance issues in B-Rep CAD and support isogeometric analysis. However, the bulk of 3D model will grow when the trivariate spline representations are used. To address this issue, effective automatic generation methods of trimmed trivariate CAD models are required.

2.3. 2D Slice representations

2.3.1. LEAF format

The LEAF format [39] is a file format (.leaf) that can be used to represent the 2D slice data for AM. It was developed for layered manufacturing processes by Dolenc and Malela. The format consists of a head section and a geometry section. The head section is used to encode the preprocessing data, which includes the definition of keywords, machine-specific data, mathematical data, and the technological data that defines the structure of hatches and supports. The geometry section is used to describe the layer-based geometry (i.e. the 2D slices) of a part model. The layer is the main entity that includes both geometric and process data and may have sub-entities such as contours, hatches, and supports. Each contour is a polygon that does not intersect with itself [50].

2.3.2. SLC format

The SLC format is a file format (.slc) that can be used to represent the 2D slice data for AM. Several AM related companies (e.g. 3D Systems, Stratasys, POGO International) have respectively developed their proprietary slice formats, which are all referred to as SLC formats. A typical example of SLC formats is the SLC format of 3D Systems [40]. This SLC format consists of successive cross-sections which are taken at ascending Z intervals. In each cross-section, solid material is described via interior and exterior boundary polylines. It supports the description of slice data from various sources, such as 3D CAD model, tessellated 3D model, and reverse engineering [155].

2.3.3. CLI Format

The CLI format [41] is a file format (.cli) that can be used to represent the 2D slice data for AM. It was developed to provide a simple, efficient, and unambiguous slice format for layered manufacturing systems by the Commission of the European Communities. In this format, each layer is described by its thickness and a certain number of contours and hatches (optionally), where contours represent the boundaries of solid material within a layer, and hatches define the support or filling structures. A contour and a hatch are respectively defined by a set of polylines and two points (one start point and one end point). The CLI format is independent of fabrication machines and the conversion from it to the internal file format of a fabrication machine is very simple.

2.3.4. HP-GL Language

HP-GL is a printer control language for HP plotters developed by Hewlett-Packard [42]. The HP-GL format (.hpgl) is based on this language and consists of a set of instructions which is called HP-GL kernel and several device specific extensions. The instructions in the HP-GL kernel are classified into configuration and status, vector, polygon, line and fill attributes, and character. Using these instructions, the HP-GL format can be used to represent the 2D sliced contours in layered manufacturing [50].

2.3.5. MAMF format

The MAMF format was developed to provide a slice based representation of geometry and materials of multi-material objects by Zhang and Joshi [43]. In this format, the combination of material index and material geometry region is used to add multi-material attributes to a sliced file. Based on this, the representation of a wide range of homogeneous or heterogeneous materials is implemented via a revised CLI format. Such representation can be directly used in the generation of tool paths for fabricating the physical object.

2.4. Integrated representations

2.4.1. STEP Standards

The STEP standards [44] are a huge set of ISO standards used to represent, archive, and exchange product data throughout the product lifecycle in traditional manufacturing. They are in constant development and consist of nearly three thousand substandards [156]. These substandards can be classified into six groups. They are description methods (from Part 11 to Part 19), implementation methods (from Part 21 to Part 29), conformance testing methodology and framework (from Part 31 to Part 39), integrated resources (from Part 41 to Part 199), application protocols (from Part 201 to Part 1199), and abstract test suites (from Part 1201 to Part 2199). The substandards developed for the purpose of product data representation are the substandards in the groups of integrated resources and application protocols. All of these substandards adopt the EXPRESS data modelling language defined in Part 11 [157] to describe the product data. The resultant files of their descriptions are STEP (.stp/.step) files, which are all encoded in a format of clear text defined in Part 21 [158].

Although theoretically all of the substandards in integrated resources and application protocols can be used to represent the product data in traditional manufacturing, most of them are not necessarily suitable for AM data representation. As can be summarised from the papers or reports of Kumar and Dutta [50], Marsan et al. [51], Lipman and McFarlane [52], Patil et al. [159, 160], Starly et al. [161], Zhou [162,163], Brangé et al. [164], Ryou et al. [165], Bonnard et al. [166–168], Um et al. [169], Rodriguez [170], and Eynard [171], the standards that have been used in AM data representation or suggested using in this domain are Part 42 [172], Part 45 [173], Part 47 [174], application protocol (AP) 203 [175], AP 214 [176], AP 238 [177], AP 242 [178], and application interpreted construct (AIC) 519 [179]. The major usage of these standards in AM data representation and their coverage of AM process activities are shown in Table 5.[3] As can be seen from Table 5, the STEP standards used in AM data representation can be classified into three groups. The standards in the first group are mainly used to represent 3D model and 2D slices, which include Part 42 and AP 242. Part 45, Part 47, and AIC 519 are mainly leveraged to represent the properties of a 3D model (e.g. material, colour, tolerances). They constitute the second group. AP 238 itself belongs to a group, i.e. the third group. It is mainly used for the representation of the data in process planning and part build.

Part 42, which is known as geometric and topological representation, allows exact representation of the geometry and topology of an object. Thus it can be used to represent 3D model and support structures. It also has the capability for exact representation of the geometry of a 2D sliced contour [50,51,159–163]. AP 242, which is known as managed model-based 3D engineering, covers all of the scopes of both AP 203 and AP 214. Additionally, it has involved the representation of more product data, such as tessellated geometry, kinematics, and tolerances [180,181]. Among Part 42, AP 203, AP 214, and AP 242, AP 242 is perhaps the best standard for AM data representation. In this standard, a set of planar triangular facets are defined via a list of coordinates and indices. Each triangular facet is located using one of its normal vectors. A tessellated solid or shell is formed via grouping multiple sets of triangular facets together. After combining all of the tessellated solids and shells of a 3D model, the tessellated geometry of this model can be achieved and represented. AP 242 also has the capability of representation of 3D model properties (e.g. material, colour, and tolerances), support structures, and 2D sliced contours [52]. It is, however not yet completely satisfactory for AM data representation. The major limitations of the standard are: (1) It does not allow the use of curved triangular facets. This may lead to the approximation accuracy issue as in the STL format. (2) It only supports the representation of single material and single colour, which is insufficient to meet the demand of representing multi-colour and multi-material objects. (3) It is slightly too complicated for AM data representation. It contains unnecessary higher order representations such as NURBS and B-Rep surfaces [122]. To overcome these limitations, the solutions presented by Patil et al. [159,160] and Zhou [163] could be effective, and the developers of the standard also considered and carried out the development of two new editions of the standard. In the second edition of AP 242 (which is currently under development and is expected to be published in 2019), curved triangles based on cubic Bezier triangles will be used to improve the approximation accuracy in geometric representation and texture mapping will be leveraged to describe multi-colour objects. This edition will also include the capabilities of representation of build orientation, build plate size, build volume, and build plate placement. In the third edition of AP 242 (whose whitepaper is currently under development), the representation of heterogeneous materials, lattice structures, and product manufacturing information for AM will be considered [182].

Part 45, Part 47, and AIC 519, which are respectively entitled material and other engineering properties, shape variation tolerances, and geometric tolerances, were suggested to be used to represent the material, tolerances, and other properties of a 3D model for AM [159,160]. Since this scope has been covered by AP 242, there is not much need to combine the three standards to implement such representation.

AP 238, which is entitled application interpreted model for computerised numerical controllers, is commonly known as STEP-NC (numerical control). It is a machine tool control language that extends the STEP standard system with the machining model in ISO 14649 [183] (this is why sometimes both AP238 and ISO 14649 are collectively called as STEP-NC), the GD&T data for inspection, and the STEP product data management model for integration. STEP-NC was developed to replace G-code [184] with an associative protocol that connects process data to a description of the part being machined. Therefore, it comes as no surprise that the research of STEP-NC in AM has gained more importance and popularity than the research of G-code in AM. Ryou et al. [165], Bonnard et al. [166–168], Um et al. [169], Rodriguez [170], and Eynard [171] have explored the way to make STEP-NC applicable for process planning for AM and part build. Meanwhile, STEP Tools has developed an open source package named as AdditiveNC [185] to parse the data in process planning for AM and part build described by a common layer interface (CLI) [41] file and create a machining program as STEP-NC. In addition, STEP-NC also supports the representation of AM part geometry, material, and colour [52]. However, it lacks the support of representing tessellated geometry, multiple materials, and multiple colours. From this point of view, it could be a good idea to combine STEP-NC with AP 242 to get a more comprehensive STEP standard for AM (such a standard has been named as STEP-AM by Xiao et al. [95]).

3 Since AP 203 and AP 214 have been withdrawn by ISO and merged and extended by AP 242, they are not included in this table.

Table 5
Major usage of STEP standards in AM data representation and their coverage of AM process activities. Notes: A_1 denotes design for AM; A_2 denotes process planning for AM; A_3 denotes part build; A_4 denotes post-processing; A_5 denotes qualification and certification.

Standard	Number	Major usage in AM data representation	AM process activity coverage				
			A_1	A_2	A_3	A_4	A_5
Part 42 [172]	ISO 10303-42	3D model, support structures, and slices	■	■			
Part 45 [173]	ISO 10303-45	Material and other properties	■				■
Part 47 [174]	ISO 10303-47	Geometric dimensioning and tolerancing					■
AP 238 [177]	ISO 10303-238	Data in process planning for AM and part build		■	■		
AP 242 [178]	ISO 10303-242	3D model, properties, support structures, and slices	■	■			■
AIC 519 [179]	ISO 10303-519	Geometric dimensioning and tolerancing					■

2.4.2. Coding system method

The coding system method [45] is a representation of AM data based on specific coding system. It was presented to code the geometric and process data of rapid prototyping parts by Ingole et al. In the method, rapid prototyping parts are firstly classified based on eight criteria, which are types of rapid prototyping processes, material of the part, type of application for which part is fabricated, accuracy of the part, overview of part geometry, shape of the part, existing features present in the part, and build orientation of the part. Then the framework of a coding system consisting of eight digits, where each digit is respectively utilised to code each of the eight criteria, is established. Based on the framework, the details of how to code the eight digits are explained via eight general steps, which respectively correspond to the eight criteria.

The coding system method is capable of helping in retrieving specific product or process data for reuse. Important data like geometry, materials, part build orientation, and part accuracy, can be derived from this method. Further, the method can be leveraged to classify AM parts according to their similarity in process and geometry. The classified part forms a tractable database which is useful for the development of rapid prototyping products. Currently, the application scope of the coding system method is only limited to representation of the data in fused deposition modelling process. The application of the method in other AM processes remains to be explored.

2.4.3. Digital thread method

The digital thread method [46] is a representation of AM data which aims to represent all types of data in AM process activities. It is based on XML file format and influenced by the AMF format. This method uses XML to synthetically encode the 3D design data in design for AM, the slice, path plan, and processing parameters in process planning for AM, the sensor data and qualification record in part build, and the verification and validation data in qualification and certification. As anticipated by Nassar and Reutzel, the method would implement the representation of all necessary data for reproducing, modelling, and validating AM parts. They also pointed out that the major challenge in the implementation is the reluctance of the manufacturers of AM machines to adopt a non-proprietary data format in their respective machine.

2.4.4. Integrated data schema method

The integrated data schema method [47] is a representation of AM data which aims to support AM data collection, storage, and usage over the entire AM value chain. In this method, an integrated AM data model based on a product lifecycle management data modelling paradigm called product–process–resource paradigm was constructed. The constructed model has a core schema consisting of product, process, and resource entities, where the process entities play important role in transforming the inputs of AM products into the outputs of AM products using the assigned resources. To demonstrate the effectiveness of the model, a prototype of implementable XML schemas based on the model was created to ground the design of an information system for AM experimental data management. The demonstration result shows that the model has advantages over the existing AMF format, 3MF format, and STEP-NC standard in both comprehensiveness and AM-specific navigable structure. However, it is currently a conceptual model. Further research work is required to extend it to a completely implementable model for actual use.

2.4.5. Unified storage file format

The unified storage file format [48] is a representation of AM data which aims to assist the accumulation of all relevant data during the development process of AM parts. It is implemented as an XML schema, a language mainly used to specify how to formally describe the elements in an XML document. This XML schema makes it possible to encode all of the input, required, lost, and output data in design for AM, process planning for AM, part build, post-processing, and qualification and certification. But its current version still lacks the support for representing data semantics and multi-material objects. This issue could probably be addressed in Baumann et al.'s future research.

2.4.6. Relational database method

The relational database method [49] is a representation of AM data based on specific relational database. In this method, the segregation and organisation of AM data are firstly explored using the materials and processing technical information system which was developed by the National Aeronautics and Space Administration (NASA). Then with the NASA's database of materials and process requirements for spacecraft [186], AM data is classified into materials, build process and parameters, post-processing data, and mechanical testing data. Based on such classification, a relational database is developed to organise and store these data. This database can facilitate the comparison of the properties across AM builds against the traditionally manufactured materials. It is expected to be leveraged to tackle the challenges regarding data management and sharing to accelerate the discovery or development of new materials for AM processes.

3. Comparisons and discussions

In this section, a series of qualitative comparisons are made respectively among the 3D model representations in Table 2, the 2D slice representations in Table 3, and the integrated representations in Table 4. Then a discussion about the main issues in the field of AM data representation is carried out to approach the research question Q5.

3.1. Comparisons

In general, a quantitative comparison among different representations of AM data is difficult to be made because the implementation details of most representations are not available and it is difficult to quantify the performance of a representation.

For this reason, the comparisons among such representations are always made in a qualitative way [50–52]. According to the reviews of Kumar and Dutta [50], Marsan et al. [51], and Lipman and McFarlane [52], a qualitative comparison is generally carried out based on a benchmark, which consists of a certain number of comparative aspects.

The benchmark designed by Kumar and Dutta [50] and Marsan et al. [51] was used to compare both 3D model representations and 2D slice representations. It consists of three categories of comparative aspects, which are neutral exchange format aspects, 3D model representation aspects, and 2D slice representation aspects. The neutral exchange format aspects include completeness, neutrality, efficiency, storage, extensibility, inspectibility, robustness, compatibility, and domain. Both the 3D model representation aspects and the 2D slice representation aspects contain type, accuracy, information, efficiency, redundancy, and repairability. The benchmark of Lipman and McFarlane [52] was used to compare 3D model representations. It only involves one comparative aspect: the coverage of AM data types. In addition to the above-mentioned benchmarks, there are also some other scholars who have given the aspects that can be used to compare different representations of AM data. For example, Pratt et al. [93] analysed that an international standard for data transfer in layered manufacturing should support the representation of geometry, assembly, tolerance, feature, and material. Hiller and Lipson [133] pointed out that an ideal format for AM data should address the concerns of technology independence, simplicity, scalability, and compatibility. Xiao et al. [95] compared the AM standard formats STL, AMF, and STEP using the description of tolerancing and compatibility of product and manufacturing information as criteria. Baumann et al. [48] pointed out that an ideal storage file format for AM should meet the demands of storing data in a single file, describing data unambiguously, containing no redundancy, and facilitating fast manipulation of files. Ameta and Witherell [187] compared the existing models for heterogeneous materials and geometry at the aspects of model type, material capability, procedural purpose, representational purpose, analysis use, and AM use.

As can be seen from the description above, a number of comparative aspects have been presented in the literature. Although these aspects play certain roles in comparing specific representations of AM data, they are not equally important. To this end, only some important aspects are utilised to separately compare the 3D model representations in Table 2, the 2D slice representations in Table 3, and the integrated representations in Table 4. The details of the comparisons are respectively explained below.

3.1.1. Comparison among 3D model representations

To compare the 3D model representations in Table 2, the aspects coverage, accuracy, redundancy, repairability, interoperability, inspectibility, extensibility, compatibility, accessibility, and application are leveraged. The results of this comparison are shown in Tables 6 and 7. The details of the comparison are explained as follows:

- Coverage: Which types of AM data does the representation cover? As can be concluded from the introduction and analysis of the eighteen different representations in Section 2, the STL, RPI, STH, and CFL formats were specifically developed or used to represent part geometry. The AMF, 3MF, OBJ, X3D, JT, SIF, SPF, PLY, and SAT formats were developed or introduced to address the issues of the STL format. They have stronger representation capability than the STL format. Specifically, they support the representation of not only part geometry, but several or all of GD&T, surface roughness, materials, colours, texture, and metadata. The non-manifold B-Rep, feature tree, and CSG methods were mainly presented for representation of the 3D objects with multiple or composite materials. The voxel and trivariate spline methods can support the representation of GD&T, surface roughness, materials, colours, and texture.
- Accuracy: How accurate is the method in terms of part geometry representation? Tessellations with only planar triangles in the STL, 3MF, and STH formats can bring relatively large approximation error, which is a major issue of these formats. The AMF, RPI, CFL, and SIF formats and the CSG method can address this issue to some extent via using both planar and curved triangles, boundary facets or CSG primitives, planar polygons, and CSG primitives and Boolean operations. The remaining representations are capable to represent part geometry in relatively high approximation accuracy since they allow the use of some high order tessellations such as free-form curves and surfaces, NURBSs, curved Steiner patches, B-Rep surfaces, voxels, and trivariate splines.
- Redundancy: How is the capability of the representation to avoid representing and storing redundant data? Another issue of the STL format is that it always represents a lot of redundant data. Overcoming this issue is one of the major strengths of the AMF, 3MF, RPI, CFL, SIF, and SPF formats. The OBJ, X3D, JT, PLY, and SAT formats also represent many types of data which are not necessary for AM since these formats were not specifically developed for AM. By contrast, the feature tree, voxel, and trivariate spline methods are specifically presented for AM, their concise is satisfying.
- Repairability: How flexible is the representation in terms of offering mechanisms or tools for correction of its errors? As listed in [122], there are various available software tools for repairing an STL file, an AMF file, or a 3MF file. Repairing the files generated by the OBJ, X3D, JT, PLY, and SAT formats and the non-manifold B-Rep and CSG methods is troublesome because they are more complicated or there are not many available repair tools. Correcting the errors in the representations of the remaining representations is the most difficult task since there are almost no repair tools available.
- Interoperability: How flexible is the representation in terms of exchanging AM data among heterogeneous systems? It is easy to implement the exchange of the AM data represented by the STL, AMF, 3MF, OBJ, and PLY formats between heterogeneous systems because these formats have been adopted in industry and many AM related systems support them. To implement the exchange of the AM data represented by the X3D, JT, RPI, STH, CFL, SIF, SPF, and SAT formats among different systems is not too difficult, because the physical manifestations of the described data are all file formats, which can be used as neutral exchange formats. By contrast, the physical manifestations of the non-manifold B-Rep, feature tree, CSG, voxel, and trivariate spline methods are not file formats, which makes it difficult to implement their interoperability.
- Inspectibility: How flexible is the representation in terms of offering assess for inspection and verification? The inspection and verification (i.e. qualification and certification) of an AM part require the data of GD&T, defects, microstructure, surface roughness, and part properties. As shown in Table 6, the JT format and the voxel and trivariate spline methods support the representation of GD&T and surface roughness. Therefore, they have relatively desirable inspectibility. Correspondingly, the AMF, SIF, and SPF formats partly support such representation. Their inspectibility can be considered as moderate. All of the remaining representations have limited inspectibility because they do not support or include the representation of the data required in the inspection and verification.

Table 6
Comparison of the coverage of the 3D model representations in Table 2. Notes: NMBR stands for non-manifold B-Rep; FT stands for feature tree; TS stands for trivariate spline.

Representation	Geometry	GD&T	Roughness	Materials	Colours	Texture	Metadata
STL format	Planar triangles	No	No	No	No	No	No
AMF format	Planar or curved triangles	Single value	No	Multiple	Multiple	2D or 3D maps	Various
3MF format	Planar triangles	No	No	Multiple	Multiple	2D maps	Various
OBJ format	Polygons or curves or surfaces	No	No	Multiple	Multiple	2D maps	Support
X3D format	Polygons or NURBSs	No	No	No	Multiple	Support	Support
JT format	Any triangles or B-Rep surfaces	Support	Support	Multiple	Multiple	Support	Support
RPI format	Facets or CSG primitives	No	No	No	No	No	No
STH format	Planar triangles	No	No	No	No	No	No
CFL format	Planar polygons	No	No	No	No	No	No
SIF format	Planar polygons	Single value	Support	No	Multiple	No	Support
SPF format	Curved Steiner patches	Single value	No	Multiple	Multiple	2D or 3D maps	Various
PLY format	Polygons	No	No	Multiple	Multiple	Support	No
SAT format	B-Rep surfaces	No	No	No	Multiple	No	No
NMBR method	B-Rep surfaces	No	No	Multiple	No	No	No
FT method	Non-manifold cells	No	No	Multiple	No	No	No
CSG method	CSG primitives and operations	No	No	Multiple	Multiple	No	No
Voxel method	A collection of voxels	Support	Support	Multiple	Multiple	Support	No
TS method	Trivariate splines	Support	Support	Multiple	Multiple	Support	No

Table 7
Comparison of the storage, accuracy, redundancy, repairability, interoperability, inspectibility, extensibility, compatibility, accessibility, and application of the 3D model representations in Table 2. Notes: NMBR stands for non-manifold B-Rep; FT stands for feature tree; TS stands for trivariate spline.

Representation	Accuracy	Redundancy	Repairability	Interoperability	Inspectibility	Extensibility	Compatibility	Accessibility	Application
STL format	Limited	Limited	Satisfying	Satisfying	Limited	Limited	Satisfying	Satisfying	Satisfying
AMF format	Moderate	Satisfying	Satisfying	Satisfying	Moderate	Satisfying	Satisfying	Satisfying	Satisfying
3MF format	Limited	Satisfying	Satisfying	Satisfying	Limited	Satisfying	Satisfying	Satisfying	Satisfying
OBJ format	Satisfying	Limited	Moderate	Satisfying	Limited	Moderate	Moderate	Satisfying	Satisfying
X3D format	Satisfying	Limited	Moderate	Moderate	Limited	Moderate	Moderate	Satisfying	Limited
JT format	Satisfying	Limited	Moderate	Moderate	Satisfying	Moderate	Moderate	Satisfying	Limited
RPI format	Moderate	Satisfying	Limited	Moderate	Limited	Satisfying	Satisfying	Limited	Limited
STH format	Limited	Moderate	Limited	Moderate	Limited	Limited	Satisfying	Limited	Moderate
CFL format	Moderate	Satisfying	Limited	Moderate	Limited	Limited	Moderate	Limited	Moderate
SIF format	Moderate	Satisfying	Limited	Moderate	Moderate	Satisfying	Satisfying	Limited	Limited
SPF format	Satisfying	Satisfying	Limited	Moderate	Moderate	Satisfying	Satisfying	Limited	Limited
PLY format	Satisfying	Limited	Moderate	Satisfying	Limited	Moderate	Moderate	Limited	Moderate
SAT format	Satisfying	Limited	Moderate	Moderate	Limited	Moderate	Moderate	Limited	Moderate
NMBR method	Satisfying	Moderate	Moderate	Limited	Limited	Moderate	Limited	Limited	Limited
FT method	Satisfying	Satisfying	Limited	Limited	Limited	Moderate	Limited	Limited	Limited
CSG method	Moderate	Moderate	Moderate	Limited	Limited	Moderate	Limited	Limited	Limited
Voxel method	Satisfying	Satisfying	Limited	Limited	Satisfying	Moderate	Limited	Limited	Limited
TS method	Satisfying	Satisfying	Limited	Limited	Satisfying	Moderate	Limited	Limited	Limited

- Extensibility: How flexible is the representation in terms of allowing addition of new features? The AMF, 3MF, RPI, SIF, and SPF formats have good extensibility, as described in their respective specifications or documents. Conversely, the STL, STH, and CFL formats have relatively limited extensibility, which has been pointed out in [50,51]. The remaining representations have moderate extensibility.
- Compatibility: How flexible is the representation in terms of allowing any of its old versions of file to be converted and allowing new features to be added as advances? The STL, RPI, and STH formats have desirable compatibility, which has been explained in the reviews of Kumar and Dutta [50] and Marsan et al. [51]. The AMF and 3MF formats are both backwards and future compatible [13,14]. The SPF format is also both backwards and future compatible because it can be regarded as an extension of the AMF format. The SIF format also has satisfying compatibility because it is backward compatible.
- Accessibility: Are the access and implementation of the representation free? As stated in the specifications of the STL, AMF, 3MF, OBJ, X3D, and JT formats [12–17], the access and realisation of these formats are free of specific aspects such as royalties, patents, and licensing. As for the remaining representations, there is yet no evidence that the access and implementation of any of them are free.
- Application: Has the representation been widely applied in the AM industry? The STL, AMF, 3MF, and OBJ formats have been used in the AM industry. Currently, these formats are respectively the first, fourth, third, and second most used representations of 3D model data in the AM industry [122].

3.1.2. Comparison among 2D slice representations

The 2D slice representations in Table 3 are compared via the aspects of coverage, type, accuracy, interoperability, extensibility, accessibility, and application. The results of this comparison are shown in Table 8. The details of the comparison are explained as follows:

- Coverage: The LEAF, SLC, and CLI formats and the HP-GL language were specifically developed for representation of 2D slices. The MAMF format mainly aims to represent 2D slices and the homogeneous or heterogeneous materials at slice level.
- Type: What is the slice representation scheme of the representation? The slice representation scheme in the LEAF format is based on polylines and circular arcs, while the schemes in the SLC and CLI formats and the HP-GL language are based on polylines. The MAMF format can be seen as a revised CLI format from the perspective of representation of 2D slices. Thus, its slice representation scheme is also based on polylines.

Table 8
Comparison of the coverage, type, accuracy, interoperability, extensibility, accessibility, and application of the 2D slice representations in Table 3.

Representation	Coverage	Type	Accuracy	Interoperability	Extensibility	Accessibility	Application
LEAF format	Slices	Polylines, circular arcs	Satisfying	Satisfying	Satisfying	Limited	Satisfying
SLC format	Slices	Polylines	Moderate	Moderate	Moderate	Limited	Satisfying
CLI format	Slices	Polylines	Moderate	Satisfying	Moderate	Limited	Satisfying
HP-GL language	Slices	Polylines	Moderate	Satisfying	Moderate	Limited	Satisfying
MAMF format	Slices, materials	Polylines	Moderate	Limited	Moderate	Limited	Limited

- Accuracy: How accurate is the method in terms of 2D slice representation? The accuracy of the LEAF format is higher than that of the SLC, CLI, and MAMF formats and the HP-GL language, because of the use of circular arcs in representation of 2D slices.
- Interoperability: It is relatively easy to implement the exchange of the 2D slice data represented by the LEAF and CLI formats and the HP-GL language, because these representations have been applied in the AM industry. To implement the exchange of the AM data represented by the MAMF formats among different systems is relatively difficult, since it is a new representation and has not yet been adopted by the AM industry.
- Extensibility: The LEAF format has satisfying extensibility, while the extensibility of the SLC and CLI formats and the HP-GL language can be seen as moderate, which has been provided in [50,51]. Since the MAMF format is actually a revised CLI format, its extensibility is also moderate.
- Accessibility: There is yet no evidence that the access and implementation of any of the five representations in Table 8 are free.
- Application: Among the five representations in Table 8, only the MAMF format has not yet been used in the AM industry.

3.1.3. Comparison among integrated representations

To compare the integrated representations in Table 4, the aspects coverage, simplicity, interoperability, extensibility, inspectibility, accessibility, and application are used. The results of this comparison are shown in Tables 9 and 10. The details of the comparison are explained as follows:

- Coverage: As summarised in Table 5, the STEP AP 242 standard is mainly used to represent 3D model, support structures, and 2D slices in AM, where 3D model includes geometry, lattice structures, GD&T (based on ASME Y14 standards), single material, and single colour. The STEP-NC standard is mainly leveraged to represent the data in process planning for AM and part build, which involves support structures and machine setup parameters. In addition, this standard also support the representation of lattice structures, GD&T (also based on ASME Y14 standards), single material, and single colour. The AM data represented by the coding system method includes geometry, single material, accuracy, and build orientation. The digital thread and integrated data schema methods and the unified storage file format have a common goal, which is to represent all necessary data used and generated throughout all activities of an AM process. These representations cover design data, process planning data, build data, post-processing data, and verification and validation data. Benefiting from the NASA's database of materials and process requirements [186], the relational database method supports the storage of materials, process setup plan, process parameters, post-processing data, and mechanical testing data.
- Simplicity: How simple is the representation for learning and using? The STEP AP 242 and STEP-NC standards were not specifically developed for AM data representation and thus contain many unnecessary specifications, which brings difficulty to understanding and implementation. The coding system, digital thread, integrated data schema, and relational database methods and the unified storage file format are relatively easy to understand and implement since they were specifically presented to represent AM data and their representation techniques are respectively simple binary digits, XML schemas, XML schemas, two-dimensional tables, and XML schemas.
- Interoperability: It is easy to implement the exchange of the AM data represented by the STEP AP 242 and STEP-NC standards between heterogeneous systems because these formats were originally developed for this purpose and many computer-aided systems support them. To implement the exchange of the AM data represented by the digital thread and integrated data schema methods and the unified storage file format is not too difficult, since the physical manifestations of the represented data are all XML format, which can be used as neutral exchange format. By contrast, the physical manifestations of the coding system and relational database methods are not file formats, which makes it difficult to achieve their interoperability.
- Extensibility: The AM data represented by the STEP AP 242 and STEP-NC standards are encoded in STEP format, and the AM data described by the digital thread and integrated data schema methods and the unified storage file format are encoded in XML format. Because of the good extensibility of the STEP and XML formats, the extensibility of them is satisfying. Extending the coding system and relational database methods requires comprehensive understanding of their principles, which is not an easy task, especially for the coding system method.
- Inspectibility: As shown in Table 9, the STEP AP 242 and STEP-NC standards fully support the representation of GD&T. Thus, they have relatively desirable inspectibility. Correspondingly, the coding system, digital thread, and integrated data schema methods and the unified storage file format partly support such representation. Their inspectibility can be regarded as moderate. The relational database method has limited inspectibility because it does not support or include the representation of the data required in inspection.
- Accessibility: There is yet no evidence that the access and implementation of any of the seven representations in Table 10 are free.
- Application: There is yet no evidence to show that any of the seven representations in Table 10 have been applied in the AM industry.

3.2. Discussion

On the basis of the review of the state-of-the-art in Section 2 and the comparisons in Section 3.1, it is thought that there are currently the following issues in the field of AM data representation:

- The represented GD&T data in the existing representations are not sufficient to support the inspection of an AM part. As shown in Tables 6 and 9, a number of representations partly

Table 9
Comparison of the coverage of the integrated representations in Table 4.

Representation	Design for AM	Process planning for AM	Part build	Post-processing	Qualification and certification
STEP AP 242 standard	Geometry Lattice structures GD&T Single material Single colour	Support structure 2D slices	–	–	–
STEP-NC standard	Lattice structures GD&T Single material Single colour	Support structure	Machine setup parameters	–	–
Coding system method	Geometry Single material Accuracy	Build orientation	–	–	–
Digital thread method	Geometry Tolerance value Multiple materials Multiple colours Texture Metadata	2D slices Process setup plan Process parameters	Sensor data Qualification record	–	Verification and validation data
Integrated data schema method	Design data Design rules Multiple materials	Process planning data	Build data Equipment	Post-processing data Equipment	Equipment
Unified storage file format	Ideal product requirements AM machine specifications Accuracy data Geometry Multiple materials	Build orientation 2D slices Process setup plan Process parameters	Machine file Material machine	Post-processing goal	Test instructions
Relational database method	Multiple materials	Process setup plan Process parameters	–	Post-processing data	Mechanical testing data

Table 10
Comparison of the simplicity, interoperability, extensibility, inspectibility, accessibility, and application of the integrated representations in Table 4.

Representation	Simplicity	Interoperability	Extensibility	Inspectibility	Accessibility	Application
STEP AP 242 standard	Moderate	Satisfying	Satisfying	Satisfying	Limited	Limited
STEP-NC standard	Moderate	Satisfying	Satisfying	Satisfying	Limited	Limited
Coding system method	Satisfying	Limited	Limited	Moderate	Limited	Limited
Digital thread method	Satisfying	Moderate	Satisfying	Moderate	Limited	Limited
Integrated data schema method	Satisfying	Moderate	Satisfying	Moderate	Limited	Limited
Unified storage file format	Satisfying	Moderate	Satisfying	Moderate	Limited	Limited
Relational database method	Satisfying	Limited	Moderate	Limited	Limited	Limited

support or support the descriptions of GD&T data. These descriptions are all based on the tolerancing standards of traditional subtractive manufacturing [95] (e.g. ISO 1101 [188] and ASME Y 14.5 [189]). Although sometimes such descriptions can be normally used in AM part inspection, they do not take into account the special characteristics of AM parts and thus may lead to various issues. According to a comprehensive investigation made by Ameta et al. [190], these issues may include build direction, layer thickness, support structure related specification, scan or track direction, region-based tolerances for complex freeform surfaces, tolerancing internal functional features, and tolerancing lattice and infills. Therefore, new GD&T models for AM are needed and the representations of the developed models should be added to the existing representations of AM data to support the inspection of AM parts.

- There is a lack of a standardised representation that is specifically developed for 2D slices, one of the most important types of data throughout an AM process. The standardisation of a representation of product data can help to maximise its compatibility, generality, and interoperability and can also facilitate its application and commercialisation [191]. Among all of the existing standardised representations of AM data, only the STEP standards (e.g. Part 42, AP 203, AP 214, AP 242) can support the representation of 2D slice data. However, these representations are not specifically developed for AM. There are currently several specialised representations (e.g. LEAF format, SLC format, CLI format, HP-GL language, and MAMF format) which can be used to represent the 2D slice data. These representations are generally vendor or developer dependent and have not yet been standardised, which greatly limits their wider application.
- There is no representation that can provide a unified format of all types of AM data. Though several integrated representations have been developed or presented and they aim to offer a unified representation of all necessary data used and generated throughout all activities of an AM process, they have not yet achieved this (see Table 9). In an actual AM process, several different representations are simultaneously needed to represent different types of AM data. Since different representations always use different formats, the AM data may be encoded in different formats. Format conversion is inevitable if the encoded AM data need to be exchanged between heterogeneous systems. In addition, if they need to be retrieved and reused, many different retrieval algorithms may need to be developed, since each format may require a retrieval algorithm.

- The existing specialised representations lack an effective AM data validation mechanism. Data validation is the checking of whether there are the lack, loss, and other changes of data. Validating the AM data encoded by a representation before transferring the data to an AM machine is an important step to reduce uncertainties in AM and ensure the quality of AM parts [7]. Among the existing representations of AM data, only the STEP standards may have such mechanism because they have intrinsic conformance checking capability [192]. The existing specialised representations, e.g. the STL, AMF, and 3MF formats, need additional extensions to include this mechanism.
- Most of the existing 3D model and 2D slice representations aim to provide an effective printing format but not a real data model, while the existing integrated representations can only provide a data model. A printing format is only used to send data to an AM machine. A data model is mainly used for the archiving, retrieval, and exchange of the data [52]. A good representation of AM data should be both a printing format and a data model. The representation models in the STL, AMF, 3MF, OBJ, X3D, JT, RPI, STH, CFL, SIF, SPF, PLY, SAT, LEAF, SLC, CLI, HP-GL, and MAMF formats are only printing formats, since this is the purpose of these representations and they only consider the representation of the data required in printing. In other words, these representations are mainly leveraged to transfer data from CAD systems to AM machines. Although sometimes they can be used to exchange data between CAD systems, the types of data they can exchange are very limited. Different from them, the STEP standards, digital thread method, integrated data schema method, and unified storage file format can provide data models but have not yet become printing formats, and only the STEP standards can be used to transfer data from one CAD system to another. The details of their respective capability in this aspect have been discussed in [180]. A common weakness of them is that the data related to design intent, such as construction history, parameters, constraints, and features, are completely lost after the exchange. For this reason, the STEP standards could not be ideal CAD data exchange methods for AM. In summary, the existing representations cannot provide a representation model that can be severed as both printing format and data model, and thus are not sufficient to satisfy the requirements of model-based engineering for AM.
- The industrial application of a representation lags far behind its development and standardisation. Several relatively good representations of AM data (e.g. the AMF format, the 3MF format) have been developed and standardised. These representations are superior to the earliest STL format at all technical aspects. However, the earliest STL format still dominates the representation of 3D model data in the AM industry, while other representations only obtain limited industrial application [122]. The reasons can be explained from two aspects. On the one hand, AM related companies will be under severe cost pressure if they completely abandon the STL format. On the other hand, global education and training programs of the emerging new representations have lagged behind.

4. Future research directions

There is one last question Q6 to be answered: What are the potential research directions of AM data representation in the future? On the basis of the discussion in Section 3.2, the following future research directions in AM data representation are suggested:

- Development and representation of new GD&T models for AM. The development of new GD&T models for AM can start with addressing the issues of the existing GD&T models in AM, which mainly include AM-driven specification issues (e.g. build direction, layer thickness) and specification issues highlighted by the capabilities of AM processes (e.g. region-based tolerances for complex freeform surfaces, tolerancing internal functional features) [190]. Recently, a new committee of ASME, i.e. ASME Y14.46, has been formed to address the specification issues highlighted by the capabilities of AM processes. After developing the new GD&T models, another task is to represent them in a specific format that can be directly interpreted by computers. According to the review of the existing GD&T representation models in [193], the representation techniques used in the representations of the existing GD&T models [178,194–203] mainly include EXPRESS, graphs, representational primitives, binary trees, unified modelling language, XML, category theory, GeoSpelling formal language, polychromatic sets, adjacency matrices, and Web ontology language. These techniques may be useful for the representation of the new GD&T models.
- Standardisations of the 2D slice representations. The first step of the standardisations is to determine which method is best suited to be standardised. This step can be completed via conducting performance analysis of the existing representations (e.g. the LEAF, SLC, CLI, HP-GL, and MAMF formats) and making comprehensive consultation with key players in the AM industry. The assessment of some existing formats carried out in [50,51] could be helpful to guide the step. After determining a representation, its standardisation always requires the actions of international organisations such as ISO and ASTM and the support of technical groups and projects focused on the standardisation of AM [94]. It is also necessary to consider whether it is possible to make the representation free in access and implementation, which can greatly promote its application.
- Representation of AM data. Most of the existing representations of AM data focus on the representation of 3D model and 2D slices. For the representation of other types of AM data, further studies are required. To develop a simple, specific, and comprehensive representation, XML [135] could possibly be an ideal representation technique, since it is a simple, universal, and widely used language, most of the commercial CAD systems (e.g. SolidWorks, Creo, NX) support the XML format, and it has been successfully applied in unified representation of the product data in conventional subtractive manufacturing [204]. When developing the representation, the usefulness of an AM data representation model, such as the support of AM data sharing, exchange, archiving, and access and the application in AM data retrieval, reuse, and analysis, should be systematically considered. The product data sharing, exchange, archiving, access, retrieval, reuse, and analysis methods reviewed in [53,180, 205–210], could be served as reference methods in such consideration.
- Validation of the encoded AM data. Although the STEP standards may have AM data validation mechanism, they are not specialised representations of AM data and they check only the conformance of the encoded data. In addition, iteratively tracking and validating whether the design requirements have been satisfied in the encoded AM data, i.e. traceability, is not supported in these standards. To carry out effective validation of the encoded data in a representation, both conformance checking and rich and robust traceability should be included in this method [7]. Since currently the specialised AMF and 3MF formats do not include an

AM data validation mechanism, future studies can focus on improving these formats with the two capabilities.

- Unification of printing formats and data models. The unification of printing formats and data models can be realised via extending the existing printing formats with the capability of representing more types of AM data or developing a unified AM data representation model that can be served for both purposes. Both ways have had supporters. For example, Nassar and Reutzel [46] presented a unified paradigm to represent and transmit data at every stage of an AM process based on the AMF format. Lu et al. [47] designed an integrated data schema for representing the data in all AM process activities. Baumann et al. [48] proposed to develop a new meta-file format that aids in accumulating all relevant data throughout an AM process. It can be seen from these examples that the ultimate goal of these researchers is to develop a unified format for AM data. But the studies are currently at the stage of conceptual models. More research work is needed to achieve this goal.
- Industrial application of representations of AM data. Whether or not a new representation of AM data is really applied in the AM industry depends on many factors. The cost of the application and the technology competition between different AM related companies are two of them. Sometimes if a company completely abandons its original representation and uses a new representation, it will be under severe cost pressure or will lose some of its technical advantages. This issue is not something that academic researchers can address solely. Researchers can promote the industrial application of an AM data representation, for instance, by improving the performance of the representation. Other things like standardising the representation, making the representation free in access and implementation, and investing the education and training of the representation, could also be beneficial.

To conclude, while AM technologies continue to be the trending research area of advanced manufacturing, it has been greatly benefited from the fast developing digital and smart technologies. The study of AM data representation is one of the fundamental steps for AM to evolve towards an intelligent era. Future smart manufacturing urges an ideal representation of AM data not only in a concise, unambiguous, agile and rigorous manner, but also should be exchanged and interpreted correctly and promptly.

Such 'ideal' representation can be considered as either subjective or in contradiction. For one thing, there is no such list that can enumerate all possible requirements. An ideal representation for one's prospective might not be ideal to others, or an ideal representation at this moment will not be ideal anymore in the near future. For another, one can argue that some characteristics of an ideal representation contradict each other, for example, how can a representation be both concise and unambiguous, and both agile and rigorous? Further, with current available technologies, even a partially fulfilment of those ideal requirements is problematic, let alone working towards an ideal representation.

A precisely controlled trade-off among those characteristics of an ideal representation could be a more realistic approach. In such case, more questions need to be considered or answered: How can we make the representation be both concise and unambiguous? How can a representation be both agile and rigorous? How to trade-off the two and more? How we quantify the effectiveness of a trade-off? Furthermore, instead of directly applying currently available technologies, developing new computer-readable languages or fundamental studies of existing languages may shine light on this matter.

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Appendix. Definition of acronyms

2D — Two-Dimensional
3D — Three-Dimensional
3MF — 3D Manufacturing Format
AIC — Application Interpreted Construct
AM — Additive Manufacturing
AMF — Additive Manufacturing File
AP — Application Protocol
ASCII — American Standard Code for Information Interchange
ASME — American Society of Mechanical Engineers
ASTM — American Society for Testing and Materials
B-Rep — Boundary Representation
CAD — Computer-Aided Design
CFL — Cubital Facet List
CLI — Common Layer Interface
CSG — Constructive Solid Geometry
GD&T — Geometric Dimensioning and Tolerancing
HP-GL — Hewlett-Packard Graphics Language
ISO — International Standardisation Organisation
JT — Jupiter Tessellation
LEAF — Layer Exchange ASCII Format
MAMF — Multi-material Additive Manufacturing File
MTL — Material Template Library
NASA — National Aeronautics and Space Administration
NC — Numerical Control
NURBS — Non-Uniform Rational Basis Splines
OBJ — Wavefront OBJect
PLY — PoLYgon
RPI — Rapid Prototyping Interface
SAT — Standard ACIS Text
SIF — Solid Interchange Format
SLC — StereoLithography Contour
SPF — Steiner Patch based File
STEP — STandard for the Exchange of Product model data
STH — Surface Triangles Hinted
STL — STereoLithography interface specification
VRML — Virtual Reality Modelling Language
X3D — eXtensible 3D
XML — eXtensible Markup Language

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