Investigating the Impact of CAD Data Transfer Standards for 3DP-RDM

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Abstract

Additive Manufacturing is set to play a vital role in the Re-Distributed Manufacturing landscape. The paradigm shift towards a decentralised approach of cloud manufacturing and dynamic production requires tighter standardisation and efficient interfaces between CAD data and Additive Manufacturing. In parallel with technology advancements, it is important to consider the digital chain of information. Although a plethora of CAD formats exist, only some are used for data transfer. The problem is that a true CAD data transfer standard for a 3DP-RDM ecosystem does not exist.

The purpose of this study is to investigate the impact of CAD data transfer standards within the 3DP-RDM landscape. It aims to investigate the impact of CAD data transfer standards within the 3DP-RDM landscape and identify required features in existing standards. The study was set up by first examining the data flow from CAD to 3D printing and reviewing established shortcomings of existing data transfer standards. Further after identifying the data transfer standards AMF, 3MF, STEP and STEP-NC as upcoming and promising replacements, their premises, objectives, contributions and advantages were reviewed. Finally, the role of 3D printing in setting up re-distributed manufacturing by overcoming tooling costs and the associated economies of scale were reviewed.

Because the aims of this research touch both on sociotechnical aspects, i.e. the impact of standards on future manufacturing, and on more technical aspects, i.e. information requirements for future standards, in this study qualitative and quantitative approaches were combined to answer the research question. Focus group interviews and a survey were conducted with 3DP and RDM experts from both industry and academia. Participants' accounts were analysed for common themes and narratives. The suitability of existing data transfer formats was examined by compiling existing and expected standard features and rating them through the AM industry and experts.

Results show the expected requirements on future 3DP-RDM data transfer standards as well as their benefits, in particular with regards to manufacturing processes of 3DP service providers, but also for customer concerns such as privacy. The study shows that the STEP-NC and AMF standards are ahead in implementing the most highly valued data transfer features. Open standards are expected to further facilitate innovation in 3DP.

This study is intended to contribute to an evaluation of existing standards and their future development and adoption. It is hoped that the results will benefit policy makers and industry leaders to be aware of the importance of data exchange standards for AM so as to pave a clear roadmap for the digital economy in RDM manufacturing.

About the Authors

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Dr Eujin Pei is the Programme Director for the BSc Product Design, and BSc Product Design Engineering course at Brunel University London with a research focus on Additive Manufacturing, Functionally Graded Materials (4D Printing) and New Product Development. He is a Convenor for the International Standards Organisation Technical Committee ISO/TC261/WG4 for Data and Design Guidelines for Additive Manufacture and committee member for the British Standards Institution (BSI) BS8888 standard for Technical Definition, BS8887 standard for Design for Manufacture, Assembly, Disassembly and End-of-life Processing and the AMT/8 Group for Additive Manufacturing. He has been Principal Investigator to numerous funded projects and He has an established track record of generating new knowledge and finding solutions for a significant impact in industry.

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Content

Abbreviations

AM	Additive Manufacturing
AMF	Additive Manufacturing Format
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CAPP	Computer-Aided Process Planning
CNC	Computer Numerically Controlled
DIF	Disruptive Innovation Festival
DSM	Design for Sustainable Manufacturing
HVM	High Value Manufacturing
MBE	Model-Based Engineering
RDM	Re-Distributed Manufacturing
RPLM	Rapid Prototyping and Layered Manufacturing
SE	Systems Engineering
SFF	Solid Freeform Fabrication
STEP	Standard for Exchange of Product data
STL	Stereo Lithography
TSB	Technology Strategy Board
3DP	3D-Printing
3MF	3D Manufacturing Format

1 Introduction

Additive manufacturing (AM), also known as 3D Printing (3DP) (Wohlers and Caffery, 2015), is a method of freeform manufacturing that uses a wide range of materials that could not be produced economically through conventional production methods (Royal Academy of Engineering, 2013; Chua and Leong, 2015). The impact of 3DP is far reaching and it has been suggested that it has the potential to alter the manufacturing landscape towards more sustainable, de-centralised and personalised means of production (Frazier, 2010; Lipman and McFarlane, 2015). In this work, the term Re-distributed manufacturing (RDM) is used to describe the rapidly changing geographies, organisational structures, value chains and distribution networks associated with advancements in material science, manufacturing capability and other ICT-based digital enabling technologies. Researchers claim an RDM landscape will result in a shift towards smaller-scale local manufacturing, caused by changes in transport and labour costs, the availability of materials and energy, the need for sustainability and access to information. Consequentially, this will drive new business models and value chains and change the dynamics of work and community with implications for industry and society.

Ford and Minshall (2015) defined a research agenda for 3DP in an RDM scenario at a workshop where key research topics being identified include software, conceptual infrastructure, and overcoming the gap between manufacturing 3DPhardware and the corresponding software and manufacturing standards. This research specifically aims to investigate the impact of 3DP-RDM data transfer standards. The purpose is to understand the potential roles of 3DP in an RDM scenario and the features that are needed in potential standards to be effective in an RDM scenario. The research questions include:

RQ1: What impact could CAD data transfer standards have on a 3DP-RDM landscape?

RQ2: Who are the users and beneficiaries of 3DP-RDM CAD data transfer standards?

RQ3: What characteristics are required to manage and utilise CAD data transfer standards for 3DP-RDM?

RQ4: Which CAD data transfer standard has the greatest competitive advantage for a 3DP-RDM landscape?

RQ5: Are there opportunities for an open architecture 3DP-RDM CAD data transfer standard?

2 Literature Review

The literature review covers aspects of RDM and 3DP data transfer standards. The aim is to understand the features of 3DP-RDM, the data interface problems with current AM production methods, and how the choice of CAD data transfer standards is influenced by practical scenarios and situations. The literature review also covers the process of data flow from CAD to 3DP and examines which standard is most widely used for data transfer. We also review existing data transfer standards in manufacturing, including their place in the design and manufacturing process and benchmark them according to the aims, advantages, drawbacks, similarities and dissimilarities among them. Although many CAD formats exist, only some of them are used in 3DP for data transfer of file information, manufacturing process and part geometry. The standards being investigated include AMF, STEP, STEP-NC, STL and 3MF.

STL is seen as the proprietary but de-facto standard in today's AM industry through frequent adoption by users and CAD software providers. STEP (ISO TC184 SC4, 2014) documents protocols for product data representation and exchange in Part 242 that covers application protocol in managing model-based 3D engineering. STEP-NC (ISO TC184 SC4, 2014) looks at physical device control, in particular for data models for computerised numerical controllers (NC) where Part 1 documents a general overview and the fundamental principles. AMF (ISO TC261 WG4, 2015a) is an XML-based format designed to allow CAD systems to describe the object geometry and with support for colour, materials, lattices, and constellations. Lastly, 3MF which is also an XML-based format was developed in parallel to the design of Windows OS with the goal of creating a seamless print control interface for consumers or manufacturers that would resolve interoperability issues. It must be noted that there are other formats such as .IGES, .NURBS, .OBJ, and .VRML which also provide varying degrees of capability, information, and accuracy for 3DP but will not be covered in this study.

2.1 3D Printing

3D Printing (3DP) is a process in which parts are produced by adding the material in a layer-wise process to achieve the full geometry of the component as opposed to conventional machining such as subtractive methods where material is removed from a block to create the desired artefact. Originally, the term 3DP had been reserved for powder solidification, with the umbrella term Additive Manufacturing (AM) used for various freeform- or layer-by-layer-manufacturing technologies (Royal Academy of Engineering, 2013). 3DP has also been referred to as Rapid Prototyping and Layered Manufacturing (RPLM) and Solid Freeform Fabrication (SFF). Today, the term 3DP is widely accepted to encompass all AM processes, and 3DP and AM are used synonymously (Ford and Minshall, 2015). For this paper, the term 3DP and AM are used interchangeably.

The BS ISO/ASTM 52910 Standard Practice Guide for Design for Additive Manufacturing distinguishes AM processes into (1) Binder Jetting as the bonding of powder materials through the addition of a liquid bonding agent; (2) Powder Bed Fusion that uses the fusion of powder materials through thermal energy; (3) Material Extrusion and Material Jetting which is the dispensing of material in place; (4) Directed Energy Deposition which is the fusion of dispensed material through thermal energy; (5) Sheet Lamination which is the bonding of sheets of material; and (6) Vat Polymerisation which is the local activation of liquid photopolymers in a vat through light.

Compared to traditional manufacturing processes such as computer numerically controlled (CNC) machining, 3DP has a number of advantages where it allows almost complete three-dimensional control over artefact geometries and material properties, thus dramatically increasing the range of feasible products with no tooling and technically produces less waste material. Manufacture of interlocking parts using 3DP eliminates the need to additional assembly processes and because it does not require specialist tooling for each part, 3DP enables local, specialised and on-demand manufacturing. Parts can be produced in real time, close to the location of consumption, and based on customer specifications. Because some raw materials are more easily procured in feeder or powder form, 3DP also simplifies supply chains (Royal Academy of Engineering, 2013). As a result of these advantages, 3DP offers the opportunities to replace conventional manufacturing methods, thus enabling the development of newer products, innovative business models, and flexible supply chains (Royal Academy of Engineering, 2013). It has hence been referred to as the next industrial revolution although many practical barriers still exist today. Commercial and industrial adoption of AM is challenged by several areas such as quality control issues, artefact reliability, and process repeatability.

2.2 The 3DP Process

In a 3DP manufacturing process, an artefact is first created as a Computer-Aided Design (CAD) model that contains the geometry of the part before being produced using one of the previously mentioned AM methods. However, there are a number of stages and processes that need to be completed to realise this physical artefact. Several scholars have attempted to define key stages of the 3DP process. For example, Nassar and Reutzel (2013) distinguish four stages. In designing stage, a digital model of the artefact is created through the use of solid-modelling CAD software or by 3D Scanning an existing object and importing the data into the CAD environment. Next, in the process planning stage, the 3D-model is translated into a set of instructions for the machine operation of the 3D-printer. In the execution stage, the 3D-printer creates the physical artefact in a layer-wise process. Finally, in the verification stage, the finished artefact is compared against the original list of specifications for inspection and validation. The definition of the four stages are considered to be general and as a result, they have been further broken down by Kim *et al.*, 2015 into further eight sub-stages linked by seven activities shown below:

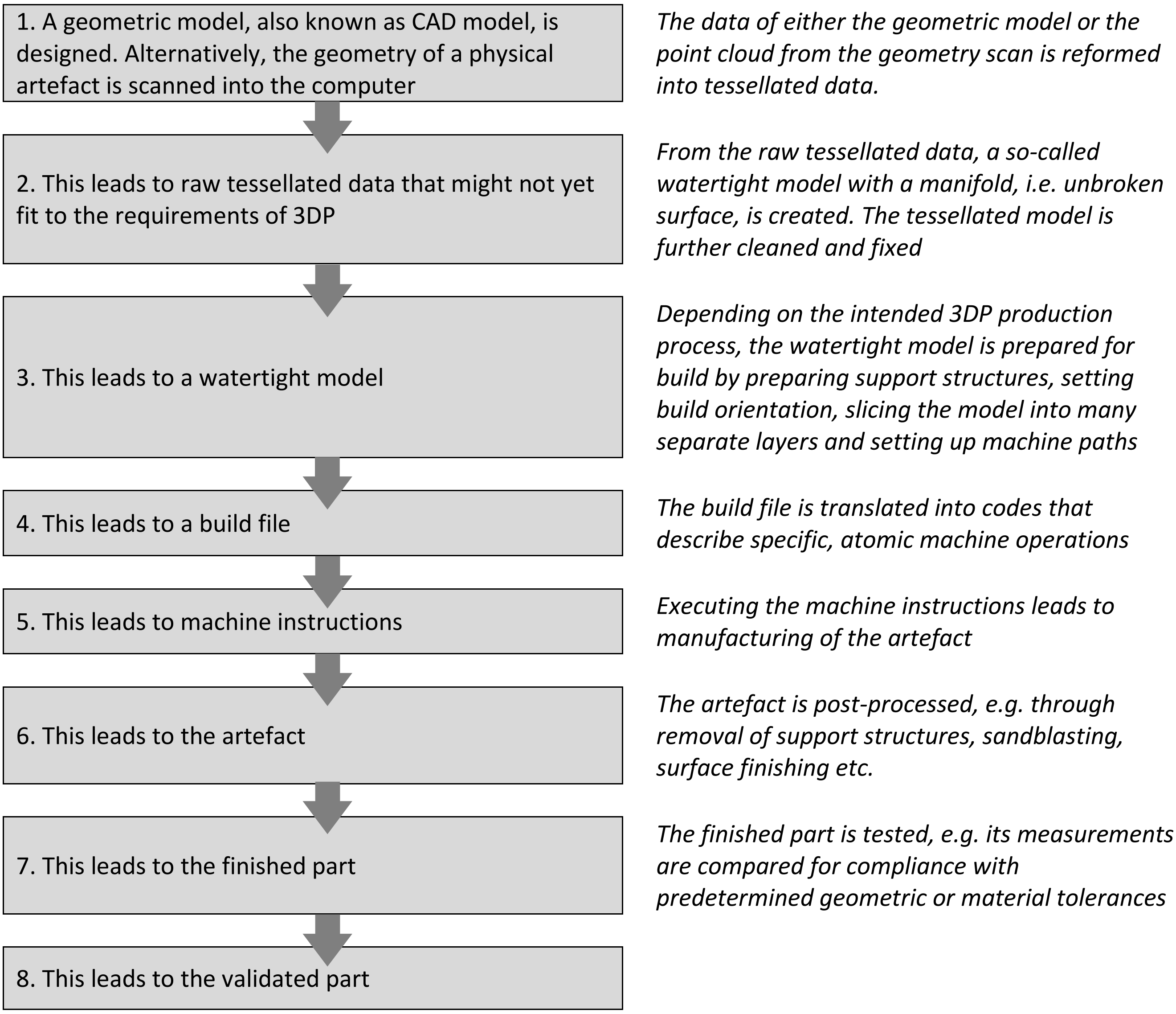

Figure 1: The complete 3DP process (Kim et al., 2015)

While those specific stages described above cover most practices observed in the industry, some steps are argued by other researchers. For example, (Pratt *et al.*, 2002) proposed skipping the creation of a tessellated model, i.e. an approximate geometric description by discrete surfaces such as triangles. Instead, slicing, i.e. the generation of horizontal layers which combined form the physical model, could be done directly from the CAD model. This would increase the precision of slices and unify the data sources for execution and verification (Lipman and McFarlane, 2015). Although tessellated models are necessary for 3DP manufacturing processes that do not follow a layer-by-layer approach, the core contribution of the process detailed by Kim *et al.*, 2015 is to understand the entire AM chain as a complete system and to approach it from a Systems Engineering point of view in order to reduce the design-to-production lead times, improve decision making through the feed of information and reduce redundancies in information acquisition to improve consistency of production. For this paper, a combined view of the 3DP process described by Nassar and Reutzel (2013) and Kim *et al.* (2015) is shown in table 2.

Stage	Sub-Stage	Activity
Part design	Geometric design	*Tesselate geometry*
	Raw tessellated data	*Create watertight model*
	Watertight model	*Prepare for build, set orientation, add support structures*
	Prepared model	*Slice model*
	Model Slices	
Process planning		*Plan paths*
	Build file	*Generate machine code*
	Machine data	
Execution		*Manufacture*
	Fabricated part	*Post-processing*
Verification	Finished part	*Testing*
	Validated part	

Table 1: Stages, Sub-stages and Activities in 3DP, from Nassar and Reutzel (2013) and Kim *et al.* (2015)

To achieve an effective print, the production requirements must be contained in the manufacturing file. Most efforts for AM file standards appear to be focused on standardising the definition of CAD geometry such as improving the STL file through the AMF and 3MF initiatives. In addition to the CAD geometry, other important build information and data requirements that are needed include object orientation, support structures, slice structures, machine paths, object packing information, and tolerance data (Pratt *et al.*, 2002). According to Hiller and Lipson (2009), a file format should consider aspects of technology independence, simplicity, scalability, and future compatibility.

For example, information such as geometry data is independent of manufacturing processes, while other information such as tool paths are dependent on the manufacturing process (Lipman and McFarlane, 2015). This means that certain information are considered to be machine or device dependent. This is particularly important for laser- and electron-beam-based AM processes where relevant data include the sequence and timing of deposition paths that influence the overall quality and composition of eventual product with regards to stress and microstructure (Nassar and Reutzel, 2013).

Other researchers have also reported that some information can be lost during the stages of manufacture. For example, the original geometry information (the native CAD file) and the tessellated features are lost after the slicing process. Slicing is used to convert a 3D CAD model into a set of instructions for the 3D printer in the form of a machine code. As there is no standard framework for the exchange of data for the AM production stages Nassar and Reutzel (2013) and Kim *et al.* (2015), propose four additional file formats in addition to the existing AMF format. The “AMSF” would specifically contain information about the “slices”; the “AMPF” extension would contain data on path planning and process parameters; “AMQF” would be used for sensor data and as a qualification record; while “AMVF” would be used in the last stages of verification and validation phase.

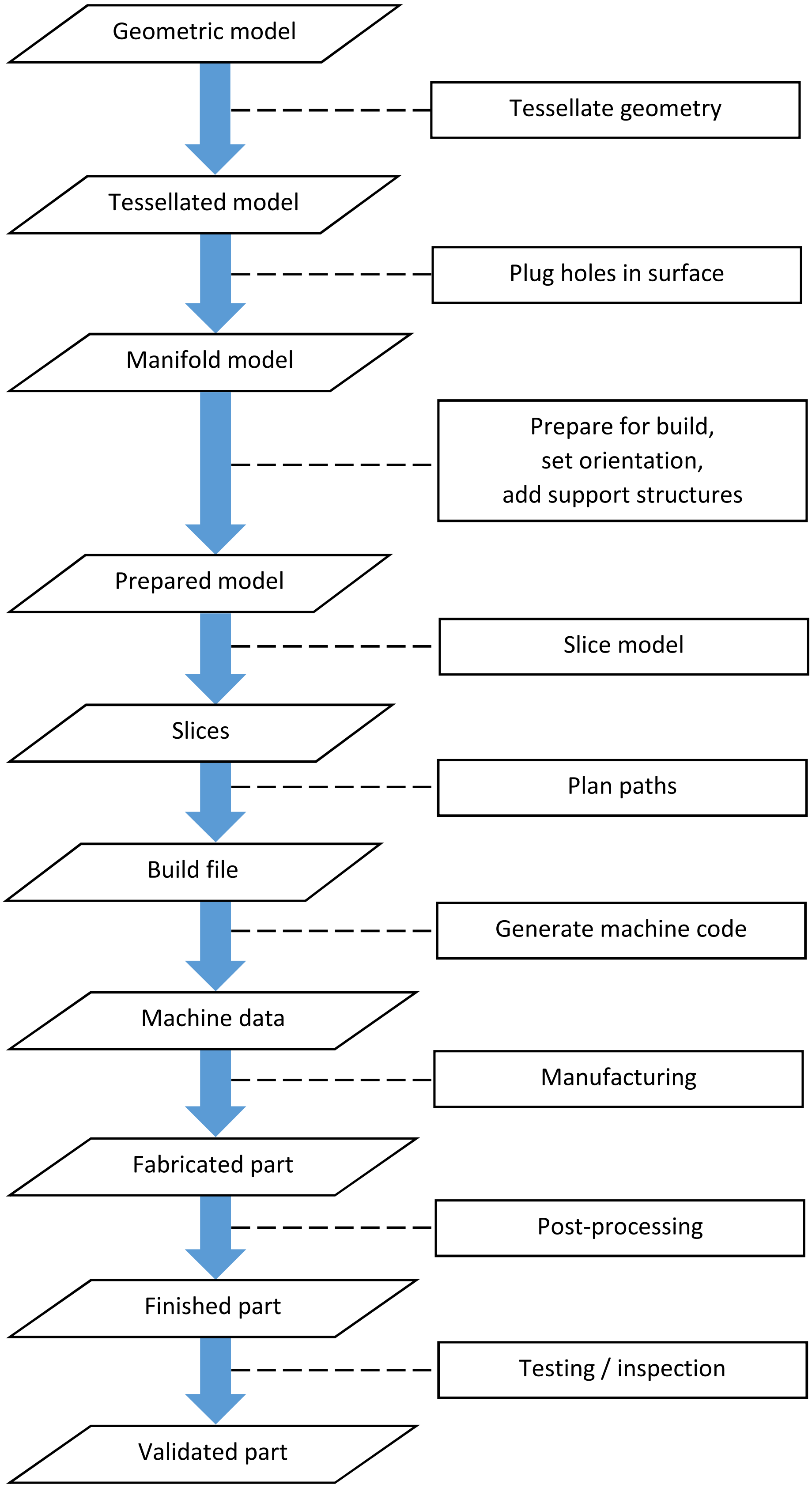

Figure 2: 3D printing process flowchart

2.3 An Overview of 3DP File Formats

Today, the most commonly used file format for transferring the data model to the 3D printer is the STL file format. STL is a digital format that is used to store tessellated surface information. It is recognised that a number of shortcomings have been identified in STL that reduce the suitability using this format for newer AM machines that are capable of having multi-nozzle and functionally-graded materials. For example, STL files are prone to redundant information and geometrical defects such as missing, overlapping and degenerate facets, guarding against and repairing of which is computationally and procedurally expensive. Further, the STL file lacks the provisions to store material, texture, colour, measurement or structural information (Chua and Leong, 2015). Further, the surface triangle information model for STL does not provide inherent mechanisms to ensure manifold surface information. As a result, a number of proprietary alternatives for 3D model storage have been proposed and efforts are underway to introduce standards to comprehensively fulfil the design requirements of AM. The most prominent effort to date is the AMF format which is recognised as an official ISO standard for AM. An upcoming alternative is the 3MF standard that arose as an effort to bridge the gap between hardware and software systems. Both are based on the extensible markup language (XML), i.e. they follow a standardised, text-based, human readable encoding format following the open XML specification (Bray *et al.*, 2008). Both AMF and 3MF are open and evolving standards that are intended to handle the large amounts of design and geometric data required by 3DP. It remains to be seen whether 3DP hardware and software vendors will refrain from proliferating their own controlled, closed-source formats or to adopt a single industry-wide framework that can cope with the complexity of different 3DP processes and machines.

In the manufacturing spectrum, an alternative approach to the standardisation of 3DP-specific file formats are STEP and STEP-NC standards. They are efforts from ISO to standardise product and production related information across a number of manufacturing processes. To date, both standards are aiming to provide extensions that can support 3D Printing infrastructure and services. Unlike STL, AMF and 3MF formats, STEP includes related geometric and tessellated model data. STEP-NC has a more ambitious aim by building on STEP to include even more process information, but avoiding the tessellated model and to only contain the geometric model. An overview of the advantages and disadvantages of the mentioned file formats is given in table 2 (Pratt *et al.*, 2002; ISO TC184 SC4 WG3, 2006; Hiller and Lipson, 2009; 3MF Consortium, 2015; ISO TC261 WG4, 2015a, 2015b, p. 261; Lipman and McFarlane, 2015; ISO TC184 SC1 WG7, 2016).

	STL	STEP	STEP-NC	AMF	3MF
Advantages	Simplicity Processing speed Portability	Flexibility Precision Manufacturing support	Precision Manufacturing support	Wide support of 3DP capabilities Manufacturing support Flexibility Extensibility Process support	Process support Sophisticated metadata support
Disadvantages	No support for modern 3DP Information redundancy Error-prone Poor scalability Inefficiency	Very complex	Paradigmatically different, no tessellated model	Large file size	Large file size

Table 2: Advantages and disadvantages of examined file formats

2.4 Data Interface Problems of Current 3DP Methods

In the previous section, we provided an overview of the 3DP process and file standards that are used in the industry. Through a literature review, we describe a number of data interface problems that have been reported among users. While we did not find any literature on context-dependency in data requirements of 3DP data transfer, there is a very clear distinction that separates the use of 3DP for rapid prototyping and 3DP as an industrial manufacturing process. In rapid prototyping, features such as exact tolerance adherence and material gradation are perceived to be of minor importance, and as such, the STL format appears to continue to be seen as sufficient for single-material prints. The current de-facto standard of using STL to describe surfaces has some shortcomings due to its inability to describe the properties of the object such as material gradation and colour. As there is an increased demand for such features to be used in 3DP, the use of STL is less capable to meet the demands of the next generation of 3DP systems. Second, while some of these issues have been addressed by newer file formats such as AMF and STEP-NC, the formats are usually software or hardware-dependent and the build files are sometimes difficult to be translated across different printer systems. Third, 3DP as an industrial process should be capable of going beyond the mere volumetric and geometric description of an artefact to be manufactured. Some production parameters have relevance to artefact integrity and need to be contained in the file for production such as built orientation or the melt pool size. Fourth, the majority of current models favour tessellated descriptions of volumes. Accordingly, a model with originally round surfaces will be represented as a number of edges and vertices. Through the tessellation process, it is inevitable that some precision is lost. Originally, tessellation seems to have been required to simplify the necessary calculations for slicing. However, processing power available in modern computing should now allow for the processing of geometric models.

Future requirements for AM file formats based on the hypothetical RDM scenario would include support for intellectual property, quality assurance, and product liability. An RDM scenario where the end user can modify parts might also take into account limited 3D modelling and engineering skill as well as capturing the knowledge between end users and conventional artefact modellers. As such, an RDM-compatible 3DP data transfer standard might have features that can be modified and other features such as the minimum and maximum wall strengths in artefacts that will be locked and cannot be edited.

2.5 3D Printing Re-Distributed Manufacturing (3DP-RDM)

To illustrate the features of 3DP-RDM, we define 3DP as a production process and RDM as an alternative manufacturing scenario that takes place in the future. The manufacturing process transforms raw materials into specifically designed physical artefacts. A number of manufacturing techniques, business schemas, and global supply chains have been established in today's landscape of modern production. Depending on the complexity of the artefact, *traditional manufacturing* is usually defined by geographically concentrated production centres that are aligned with the supply chain network. In such manufacturing centres, large amounts of generally identical items are produced for mass consumption and shipped to remote locations. The position of manufacturing centres is also subject to the availability of technology and manpower although in modern times, the aspect of shipping has become a key factor in the face of the relative efficiency of economies of scale - it is cheaper to ship products than to set up additional production plants.

Industrial development has been predicted to move away from cheap mass production towards customised and personalised products, and a changing manufacturing industry where industrial capacity can be re-allocated into reconfigurable factories for continually changing supply chains, super factories for complex products, and for domestic production (Foresight, 2013). Accordingly, five strategic themes have been identified for the future of manufacturing in the UK by the Technology Strategy Board (TSB), focusing on resource efficiency, manufacturing systems, materials integration, manufacturing processes, and business models. Manufacturing systems and processes in particular refer to the creation of more efficient and effective manufacturing models by developing new, agile, increasingly cost-effective manufacturing processes. There is potential for manufacturing to become even more flexible and adaptive, specifically by applying Additive Manufacturing and to emphasise on high-value manufacturing (HVM), i.e. “the application of leading-edge technical knowledge and expertise for the creation of products, production services and associated services” (Technology Strategy Board, 2012, p. 10), as well as “the reduction of material and energy use in production, and the repatriation of on-shoring of production” (ibid).

A part of this is a trend towards *distributed manufacturing*, which is an “on-demand, local manufacturing, made possible by combining digital technologies with new production processes” (EPSRC, 2013). Distributed manufacturing does away with manufacturing centres. In this scenario, manufacturing is de-centralised and the final product is manufactured close to the eventual customer. This leads to the concept of *Re-distributed* Manufacturing (RDM). RDM is defined as technology, systems and strategies that have the potential to change the economics and organisation of manufacturing, particularly with regard to location and scale (Pearson, Noble and Hawkins, 2013). RDM represents the production of evolved, smart and sustainable products, designed and produced locally using customer input and collaboration. As such, RDM poses forward social, technological and economic challenges. One of the key challenges for RDM is how to enable competitive local production, presumably through the consumer or small local manufacturers. In this context, 3DP has been identified as a technology that might lead to new business models (Wohlers and Caffery, 2015) and disrupt the current dominance of cheap global shipping and economies of scale since the principle of 3DP as a machine that can in principle produce anything eliminates the need for specialised manufacturing facilities and reduces the efficiency advantage of scale economies. While there are limitations of 3DP that cast doubt on the notion that it might replace mass-production technologies for serial manufacturing of cheap items (Holweg, 2015), it is still conceivable that 3DP would feature prominently in a combined approach where modern and smart products are modularised, with complex or consumable parts produced in traditional manufacturing, and personalised parts produced by local manufacturing or consumers. Based on this, features of a 3DP-RDM manufacturing environment are defined as follows:

- Manufacturing of adapted, customer-configured or individualised artefacts close to the customer location, potentially even by the user at home
- Iterative development and manufacturing including the end user or customer
- Truly global, de-centralised manufacturing

This would lead to a number of conceivable use cases for use of 3DP in an RDM scenario. Thiesse et al. (2015, p. 142) refer to this as: "A company constructs functional product parts whereas the customer contributes the product design. The production is then carried out by a service provider.” On one end of the user spectrum, a user might download a desired 3D model for free or for a fee. On the other end, a user might completely model a desired artefact autonomously. In between exists a scenario where a downloaded model is adapted to fit into the user’s needs. The final model is printed either by the user on his or her own 3D printer, or through a printing service, depending on the printer availability and the product requirements such as the material, resolution or quality. For example, FDM printing might be available for some users and sufficient for a number of artefacts, whereas powder-based printers or those utilising lasers might be more suitable for high-quality or high performance parts that are less likely to be at the disposal of typical end users. However, hybrid solutions are also conceivable where only some parts, specifically those that are customisable, are modified and printed by the end user, whereas the core part is manufactured remotely (Charnley, Theodoulidis and Zaki, 2015). Commercial and non-commercial model repositories such as thingyverse (www.thingyverse.com), Shapeways (www.shapeways.com), Ponoko (www.ponoko.com), or Sculpteo (www.sculpteo.com) and other printing vendors are some of those that already exist.

3 Empirical Methodology

The empirical part of this research aims to determine who are the users and beneficiaries of 3DP-RDM CAD data transfer standards, what characteristics are required of CAD data transfer standards in a 3DP-RDM scenario, which of the existing CAD data transfer standard has the greatest competitive advantage a 3DP-RDM scenario, how such standards could affect the 3DP-RDM landscape, and whether there are opportunities for an open architecture 3DP-RDM CAD data transfer standard.

A central challenge for this research's empirical method is the choice of method type. 3DP is an existing technology and its use an actual, measurable phenomenon and the use and the data requirements of 3DP is open to scientific enquiry. However, this research is not concerned with the data exchange standard requirements of today's 3DP. Instead it aims to determine the data exchange standard requirements of 3DP in a future RDM scenario. RDM is based on a hypothetical future scenario envisaged by expert assumptions or predictions. In addition, there are is not just one clearly defined RDM scenario. Instead, it appears that the shape of an RDM scenario has been interpreted differently depending on the respective experts' area of research. It must then be considered that 3DP-RDM is not an entirely technical topic. RDM in particular includes the involvement of customers and/or users, and implies that they have an impact on the artefact through personalisation or individualisation. In this context, it might be important to consider the socio-technical implications of customer/user involvement. Since common development and analysis techniques are vague, it was instead decided to obtain a view of the needs of a possible 3DP-RDM data exchange format from academics and experts in the area of 3DP and RDM via survey and focus groups. As the analysis included qualitative methods, expert interviews were planned for validation and verification of the results.

The survey was constructed to answer research questions RQ1 to RQ5. These research questions concern belong to two conceptually distinct areas of 3DP-RDM data transfer standards. Questions about impact as well as users and beneficiaries of 3DP-RDM data transfer standards are relatively open due to RDM being a future envisaged scenario. These questions require subjective predictions on two counts: first, a prediction of how RDM as a manufacturing scenario will occur, and second, how 3DP data transfer standards will fit into such a scenario. Further, RQ3 is methodologically conducive to RQ1: an opinion on the impact of data transfer standards would also imply the latter's users and beneficiaries. On the other hand, questions about the competitive advantages of existing, and required characteristics of potential, data transfer standards in the context of 3DP-RDM are at least in part anchored in actual capabilities, requirements and limitations of existing data transfer standards and of 3DP. Further, RQ5 is also conducive to RQ2: once the required characteristics for a 3DP-RDM standard have been identified, these can be used to evaluate against existing standards. Due to the abstract nature of the survey, i.e. its focus on a future scenario and its lack of connection to current practice, it might be challenging to retain a high response rate. To facilitate a response rate as high as possible, it was therefore decided to create a short and concise survey. For the rating, participants were given the option to rate each feature on a scale from "unimportant" to "very important", with "somewhat important" and "important" as intermediary options. For later analysis, these options were weighed from 4 (most important) to 1 (unimportant). Alternatively, the option "feature unclear" was available for participants felt they were not able to rate a specific feature. The survey closed with two biographical questions for qualifying the sample, i.e. country of residence (Q7) and occupation (Q8), and optional name (Q9) and email address (Q10). The complete survey is shown in appendix A.

The survey started with a question whether the respondent had heard of re-distributed manufacturing before (Q1) in order to contextualise the RDM-specific questions of the survey. This was the only point in the survey where the term RDM was specifically mentioned, as it was assumed that participants, particularly those from industry and non-academic areas might not be familiar with it. The term might also be easily misunderstood.

The next question asked what data standards that the respondents are using (Q2), and why (Q3). These questions were used as warm-up question due to their potential to augment the answers on current data transfer use, its reasons and its issues. In order to elicit from participants their views and opinions on the impact (RQ3), including users and beneficiaries (RQ1), of data transfer standards on 3DP-RDM, the survey progressed with a paraphrased description of an RDM scenario and asked how, in such a scenario, a data exchange standard would affect AM processes (Q4) and the AM industry (Q5). Q3, Q4 and Q5 would be analysed following qualitative thematic analysis, i.e. the identification of common themes.

No.	Feature	Definition
1	Arbitrary metadata	Provisions that allow for the storage of arbitrary data as deemed by the designer
2	Colour textures	The ability to define and represent printed surface patterns
3	In-material colours	The ability to define and represent colours of print materials
4	Compression	A definition on how to increase information density or reduce overall file size for archiving or transmission purposes
5	Encryption	A definition on how to protect model and product data from reading or editing by non-authorised parties
6	Copyright information	An ability to explicitly define copyright information related to the artefact representation as part of the standard
7	Curvature representation	The ability of the artefact to represent non-flat surfaces precisely instead of approximately
8	Geometric representation	The ability to store an artefact's representation through geometric approximations such as vectors or triangles
9	Manufacturing tolerances	Features that explicitly define target envelopes for physical artefacts
10	Material gradation	The ability to represent gradual changes in material property such as a gradual graduation from one material to another
11	Multiple object support	The ability to define more than one artefact in a file
12	Multi-user editing	The ability for users to simultaneously design or edit an artefact model
13	Object instance support	The ability to replicate identical geometries by referencing a previously defined geometry
14	Print queues	Features that explicitly refer to printer job management
15	Regular internal structures	The definition of internal separate from the geometric representation of the artefact, e.g. by defining these structures' triangles separately as part of the normal geometrical representation of the artefact
16	Surface structures	The definition of surface structures separate from the geometric representation of the artefact
17	Tool paths	The explicit definition of machine movements during manufacturing such as extruder or melting laser passes
18	Units of measurement	Explicit dimensions as part of an artefacts' representation
19	Voxel representation	The provision to store artefact geometry as regionally delimited three-dimensional pixels in a regular grid

Table 3: 3DP features for rating

In order to determine the characteristics required for a 3DP-RDM data transfer standard (RQ5) and the standard with the greatest competitive advantage in an RDM scenario (RQ2), participants were asked to rate various features of 3DP for importance in an RDM scenario (Q9). To keep the survey short, this was designed to fit into a single A4 page and limited the rating to 20 features related to an RDM scenario. Within the 20 features, the first of those were suggested from RDM scenarios and the respective literature. For example, customisation and user involvement features in RDM scenarios (e.g. Charnley, Theodoulidis and Zaki, 2015) and this was understood as a major requirement for a data transfer standard leading to the item "multi-user editing". The other selected RDM-related features were "copyright information" and "encryption". Additionally, the item "open architecture" was included in the list to understand how participants judged the need for an open standard (RQ4). The remaining features were populated by the most prominent factors discussed in academic literature on 3DP and its file formats and standards, as well as standard definitions (Hiller and Lipson, 2009; 3MF Consortium, 2015; ISO TC261 WG4, 2015a, 2015b), as shown in table 3.

Participants were recruited at a number of academic and industrial events related to 3DP and RDM, such as at the ISO STEP-NC meeting in Baltimore, October 2015; the Formnext industry fair in Frankfurt, November 2015; the 3DP-RDM workshop in Cambridge, January 2016; and at an ASTM/ISO meeting in West Conshohocken, January 2016. Information on these and other events and how they informed our research is summarised in Appendix C. An overview is given in table 4. Additional participants were recruited from the professional and personal network of researchers. The recruitment strategy led to a non-probabilistic sample of experts in the areas of 3DP and manufacturing, including accomplished researchers and practitioners.

Event	Date	Activity	Purpose
ISO STEP meeting	Oct. 2015	standardisation meeting	participant recruitment, information exchange
Formnext Frankfurt	Nov. 2015	industry fair	participant recruitment, information exchange
RDM|RSC workshop	Dec. 2015	workshop	Information exchange
3DP-RDM dissemination workshop Cambridge	Jan. 2016	workshop	participant recruitment, data collection, research approach dissemination, information exchange
ASTM F42/ISO TC261 joint meeting	Jan. 2016	standardisation meeting	participant recruitment, data collection, preliminar results dissemination, information exchange
DSM seminar	Apr. 2016	seminar presentation	result dissemination
ASTM F42/ISOTC261 joint meeting	Jul. 2016	standardisation meeting	result dissemination and discussion

Table 4: Attended events

4 Results and Discussion

The survey was handed out as a paper copy to 21 attendants during a meeting at the ASTM/ISO session in January 2016 with six participants completing the survey on paper. Additionally, the survey was sent as an interactive document as email attachment to 132 attendants recruited at the events listed above and other 15 attendants of the ASTM/ISO meeting who did not returned the paper copy. Eleven declined to participate, citing as reason a lack of competence in either 3DP or RDM (n=9), a lack of time (n=1), or company policy (n=1), and 19 returned a completed survey. Altogether, paper and email submissions resulted in 27 completed surveys. Additionally, two focus groups were conducted with RDM experts in a 3DP-RDM workshop held in Cambridge. One expert interview was conducted in London for validation of the results.

Of the survey participants, ten were residents of Europe, nine of North America, and four from South East-Asia. Occupationally, the sample was balanced with engineers and researchers each comprising seven participants of the sample. Further, six participants were managers, and 1 participant worked in a sales position. Two participants did not disclose their occupation. No biographical data was collected from the focus group participants. Two thirds of the participants (n=15) had heard of RDM, and for the remaining participants (n=8) the term was new. In the survey, all participants answered Q1 and Q2, two participants did not answer Q3, three participants did not answer both Q4 and Q5, and two additional participants did not answer Q5. All participants completed the rating (Q6) and gave their country of residence (Q7). One participant did not state an occupation (Q8). Almost every participant was actively using STL. Other standards in use were OBJ, AMF and STEP. A number of standards were used by only single participants, there were 3MF, CLI, IGES, MAGICS, MGX, RP, VML, and ZPR.

	STL	OBJ	AMF	STEP
Participants	26	5	3	2

Table 5: File formats used by participants

Q3 asked for the motivations of file format choices. Ten participants stated that they choose based on compatibility in the sense of portability between applications and hardware. Five participants stated that their choice is forced by one particular piece of hard- or software that will only allow this format. Only two participants chose their file format each for usability reasons such as file size or ease of use, or because either customers or superiors required them to.

	Compatibility	Hard- or software requirement	Format properties	Usability
Format choice	11	6	3	2

Table 6: Motivations for participants' file format choices

Detailing the responses of Q6, the average rating over all features was 3.01, i.e. on average each feature was rated as "important", with nine of the 20 features rated above average importance. The highest rating was "regular internal structures/lattices" with an average of 3.61, the lowest was "print queues" with an average of 2.44. Eleven of the 20 features received at least one "feature unclear" rating, with "object instances" being the most unclear feature. The complete descriptive statistics are shown in table 7.

RQ1: **What impact could CAD data transfer standards have on a 3DP-RDM landscape?** - This question was answered by a qualitative text analysis of the survey questions Q4 and Q5. Half of the participants (n=13) stated that a 3DP-RDM data transfer standard would improve the manufacturing process in 3DP, mostly through overall simplification, being able to automate the tessellation step, respectively the step from CAD to printable model (n=5), and a decrease of variation among artefacts from identical data (n=4). Four participants stated that a data transfer standard would aid in general manufacturing improvements such as the homogenisation of interfaces for manufacturing machines or bridging the AM-SM gap, a speed-up of the manufacturing process and an increase in process flexibility.

Software and hardware compatibility were seen by five participants as a transformative outcome for the 3DP-RDM landscape. Participants predicted the standardisation of data transfer formats to make possible future improvements of 3DP in auxiliary areas such as model optimisation and analysis through an adopted standard's ability to address the entire market (n=5). Further, the impact on the industry was seen by participants through a future adoption of 3DP in additional areas of manufacturing (n=5), an active involvement of end users in manufacturing (n=3), and enabling even more possible hardware geometries (n=2). An improvement of 3DP model representation, possibly through alternatives to tessellation was expected by three participants, and a better coverage of information required for a 3DP manufacturing process by two. Further individual expected and predicted benefits of a 3DP-RDM standard were a promotion of location-independent manufacturing, improved collaboration across disciplines, increased competition in the sector of 3DP service vendors, and an improved reputation of 3DP.

RQ2: Who are the users and beneficiaries of 3DP-RDM CAD data transfer standards? – This question was answered by identifying the users and beneficiaries of Q4 and Q5 in the participants' responses. A vast majority of responses suggests that manufacturers, i.e. the producers of 3D-printed artefacts, are the main beneficiaries of 3DP-RDM data transfer standards (n=20). These are followed by end users (n=8) and tool providers (n=6). Tool providers such as developers of mesh optimisers would profit from the easy access to an official standard as well as the possibility to reach the entire market by supporting a single, comprehensive standard supporting the whole range of 3DP. End users, i.e. the eventual benefactors of 3D-printed products, would profit from a number of effects, including more arbitrary artefact shapes and consideration of exclusive end user concerns such as privacy in the case of 3D-printed medical prostheses. Industrial customers were identified as beneficiaries (n=9) through an improved access to 3DP and an increased ability of 3DP to produce arbitrarily shaped products. Individual participants further identified the general public (n=3) as benefiting through a reduced impact of 3DP-RDM production, and finally developers of 3D printers (n=2) through further improvement of 3DP technologies, both enabled through standards.

	Mean	Median	Mode	uncl.	STL	AMF	3MF	STEP	STEP-NC
Internal structures/lattices	3.67	4	4	0		✓			
Manufacturing tolerances	3.56	4	4	0		✓		✓	✓
Geometric representation	3.52	4	4	0	✓	✓	✓	✓	✓
Curvature representation	3.48	4	4	2		✓			✓
Units of measurement	3.44	4	4	0		✓	✓		✓
Material gradation	3.37	3	3	0		✓		✓	✓
Surface structures/textures	3.37	4	4	0		✓			✓
Multiple objects	3.22	3	3	4		✓	✓	✓	✓
Object instances	3.16	3	3	8		✓	✓		✓
Open architecture	2.92	3	4	1		✓	✓	✓	✓
Copyright information	2.85	3	2	1			✓	✓	
Compression	2.81	3	3	1		✓			✓
Tool paths	2.76	3	3	2					✓
Voxel representation	2.72	3	3	2					
Encryption	2.72	3	3	1					
In-material colours	2.63	2	2	0		✓	✓	✓	✓
Arbitrary metadata	2.63	2.5	2	3		✓	✓		✓
Multi-user editing	2.58	2.5	2	3					
Colour textures	2.42	2	2	1		✓	✓		✓
Print queues	2.24	2	1	6			✓		

No. of supported features	0	13	9	7	14
Supported features (weigh./avg.)	0	13.53	8.40	7.26	14.43
Supported features (weigh./mod.)	0	42	23	22	44
Supported features (weigh./rank)	0	0.74	0.32	0.41	0.78

Table 7: Rating results compared to format features

RQ3: What characteristics are required to manage and utilise CAD data transfer standards for 3DP-RDM? - The five features deemed most important by the participants were regular internal structures / lattices, manufacturing tolerances, geometric representation, curvature representation, and surface structures. The full rating result, ordered by average rating, is shown in table 7. Some participants used the free text fields to express their expectation that a future 3DP-RDM data transfer standard would come with features enabling copyright and privacy protection, the latter in the context of bespoke medical artefacts such as prostheses.

RQ4: Which CAD data transfer standard has the greatest competitive advantage for a 3DP-RDM landscape? - Table 5 lists the rating results ordered by average and the supported features per standard. In order to determine what standard has the greatest competitive advantage, the standards themselves need to be ranked. We adopt the gold-first ranking, whereby the standard supporting the most important feature is ranked highest. In the event of a tie, support for the next-most-important feature determines the ranking, until there is a clear ranking. However, such a ranking would ignore the number of features actually supported – it is conceivable that a standard supporting all but one feature might lose out to a standard supporting only that one feature, which by chance has been ranked highest. So, alternatively, it could be desirable to rank the standard highest with the most supported features. Yet another alternative would be to apply a weighed ranking, where each feature is assigned a weight, e.g. according to its rank, its average importance, or its importance mode. The last four measures are shown in table 5.

The most important feature, regular internal structures, is only supported by AMF. Overall, however, STEP-NC covers more features than AMF, 3MF or STEP, and is also ranked above AMF when weighed by average feature importance, modal feature importance, or feature rank. The research suggests that the data exchange standard most suitable for a 3DP-RDM scenario is STEP-NC. This is paradoxical insofar as the STEP-NC standard is still in the process of standardising interfaces for machining and industrial scale production for AM. Beyond the question whether the STEP-NC standard should have been eligible for comparison in this research to begin with, the research results can be seen as a tentative suggestion that STEP-NC already supports a wide range of features that are rated desirable. AMF and the fairly new 3MF were expected to come out on top in the competitiveness ranking. While AMF came second to STEP-NC only marginally, 3MF did not perform well, although some of its features are supported neither by AMF nor STEP-NC. Overall, however, it appears that in their current versions, AMF is more sophisticated than 3MF.

RQ5: Are there opportunities for an open architecture 3DP-RDM CAD data transfer standard? - In the focus group sessions, it was acknowledged that commercial interests might always drift towards proprietary standards. At the same time, focus group participants emphasised that standards need to be accessible across disciplines to make them work in the context of RDM. This seems to indicate a meaning for "open" beyond merely being a synonym for unconstrained. "Open architecture" was rated 2.92 on average, somewhat below the overall average "important" rating. Only one participant did not rate the feature. The mode, i.e. most common rating, for "open architecture" was 4 ("very important"), and it is the feature with the biggest gap between average and mode. It is thus noteworthy that, compared to all other features, participants were unusually split in their opinion on open architecture. Altogether, "open architecture" received 10 ratings of "very important", and 7 ratings each for "important" or "somewhat important", but also 3 ratings for "unimportant". This is only matched, respectively surpassed, by "multi-user editing" and "print queues", which received three respectively four such ratings, and were rated much less important overall. The topic of open architecture did occur in the open text answers of Q3 and Q4, however. Two participants predicted open standards to reduce the barrier of entry for the developers of software tools and auxiliaries, leading to more competition among existing software tools such as mesh optimisers, and even to development of new, as of yet unknown improvements to 3DP through software.

5 Conclusions

This research extends our understanding of the requirements of 3DP in an RDM scenario. As RDM is a hypothetical scenario, the information requirements were developed from views solicited through a survey and focus group sessions from academics, researchers and practitioners in the field. The results show that the establishment of a data transfer standard for 3DP in an RDM scenario has the potential for positive impact on the 3DP process, mostly directly benefiting practitioners of 3DP technology. Further, a robust and comprehensive standard might facilitate ongoing development of 3DP technology. Research results also show the importance of including features for manufacturing processes and requirements as well as artefact representation in a future 3DP-RDM data transfer standard.

The rating results for a 3DP-RDM data transfer standard suggests that the information requirements are not widely divergent from today's 3DP use where the more important features focus on efficiency and effectiveness of the digital artefact representation and its general transformation into a physical product. Similarly, the most common themes in the open survey questions seem to be generally applicable to 3DP. While it is possible that the rating is specific to the RDM scenario, it seems likely that it was understandably difficult for practitioners to consider information requirements from a hypothetical point of view. It also raises the question whether there actually are RDM-specific requirements on a data transfer standard, and if yes, how relevant these features are. For example, as discussed earlier the stipulation of user-configured manufacturing as part of RDM suggests multi-user editing as a requirement for 3DP information. However, it might be that the best location to handle this and other requirements stipulated by RDM is in the software.

An assessment of information requirements in this research was further complicated by the different interpretations possible and available for an RDM scenario. We have observed a number of different views of RDM scenarios with varying features. While there are common themes, naturally the view of RDM is shaped by the research disciplines contributing to existing work. Accordingly, in some views the RDM scenario is primarily shaped by a breaking down of geographically close manufacturing centres due to a reduced need for tooling and other upfront cost. Other views focus on a re-shoring of manufacturing jobs due to reduced economies of scale. Yet other views assume reduced ecological impact through increased product life spans through individualisation. Views of the impact of RDM on technology, economy and society are diverse. Overall, more participants had knowledge of RDM than assumed at the start of the research, but the interpretive diversity necessarily impacts the homogeneity of predicted information requirements.

Our research results contribute an understanding of the expected aims and objectives as well as the beneficiaries of a future, comprehensive data exchange standard for 3DP-RDM. Specifically, such a standard is most likely to improve the manufacturing process. There is a strong emphasis on the technical capabilities of such a standard, with human and sociotechnical aspects of 3DP finding less consideration. Accordingly, these results benefit developers of future 3DP data exchange standards as well as, indirectly, 3D-printer operators. This research suggests that the software side of 3DP, and here in particular data transfer, is still in an infancy stage. It was shown that STL is the de-facto standard due to technological legacy, but that it is desirable and important in any way to move past this data transfer format to further progress 3DP through development and adoption of a more standardised medium of data transfer. It is this research that provides the groundwork through an empirically supported insight that considers the aspects and properties for future development of 3DP data transfer standards.

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Appendix A: Survey

Q1: “Have you heard of redistributed manufacturing before?”

Q2: “What file formats are you using to pass 3D model information to a 3D printer (e.g. STL, AMF, OBJ, …)?”

Q3: “If applicable, what was the reason for the file format choice?”

Imagine a future in which additive manufacturing and 3D-printing have transformed the manufacturing industry and a standardised data transfer file format such as AMF, 3MF, STEP, STEPNC or STL has succeeded so that 3DP service providers, 3DP modelling and processing software, and all 3D printers could process the same file format.

Q4: “… how would a data exchange standard have changed 3D printing and AM manufacturing processes?”

Q5: “… how would a data exchange standard have changed the 3DP manufacturing industry?”

Q6: “A large number of different file formats are used to send CAD data to 3D-printers. For this research, potential and proposed standards for CAD data transfers were analysed. This research aims to understand how important these features are for a future in which additive manufacturing has transformed the manufacturing industry. To this end, please rate the importance of each feature on a scale from unimportant to very important.

- Please follow the instructions and read each question carefully before answering.
- Rate the features speedily and in the given order. Don’t skip any features.
- If none of the answer options fit perfectly, choose the one that comes closest.
- Don’t worry if you are not sure about the precise meaning of a feature. Make a guess and follow your instincts. If you are absolutely uncertain, mark a feature as unclear.
- There are no “right” or “wrong” answers.

	unimportant	somewhat important	important	very important	feature unclear
In-material colours					
Colour textures					
Surface structures / textures					
Regular internal structures / lattices					
Material gradation					
Compression					
Units of measurement					
Copyright information					
Encryption					
Print queues					
Curvature representation					
Manufacturing tolerances					
Arbitrary metadata					
Voxel representation					
Geometric representation					

Object instances					
Multiple objects					
Multi-user editing					
Open architecture					
Tool paths					

Q7: “What is your country of residence?”

Q8: “What is your occupation?”

Q9: “What is your name?”

Q10: “What is your email address?”

Appendix B: Focus Group Instructions

Introduction:

Thank you for your participation. The aim of this research is to understand details of the contribution 3D printing can make to re-distributed manufacturing.

3D printing is the manufacturing of artefacts in layers directly from digital 3D model data. 3D printing has the advantage of requiring no special tooling, enabling individualised products, and being mostly unaffected by economies of scale.

Re-distributed manufacturing (RDM) is a scenario in which location and scale of manufacturing is changed through technologies, systems and strategies. The EPSRC has Identified as aspects of RDM localised manufacturing, flexible manufacturing, resilient manufacturing, sustainable manufacturing, resource efficient manufacturing, re-configurable manufacturing, and replicable manufacturing.

Among others, the following characteristics of 3D printing might be relevant for re-distributed manufacturing:

- Most materials, e.g. plastics, metals, ceramics, wood or glass, can be used for 3D printing.
- Artefact shapes for 3D-printed products have fewer limitations than in conventional manufacturing.
- Artefacts can be designed on a computer and then printed immediately without need of tooling or specialist manufacturing knowledge.
- Depending on material and use, many 3D printers are in size somewhere between a crate of beer and a top-loading freezer. Some industrial printers can be the size of a van.

Instructions:

We are particularly interested in how you see the role of 3D printing in RDM. To this end, we would like you to discuss the following:

- Is openness, e.g. open standards, open formats, open software etc., a particular part of RDM?
- How can 3D printing help achieve the previously mentioned aspects of RDM:
    - localised manufacturing
    - flexible manufacturing
    - resilient manufacturing

- sustainable manufacturing
- resource efficient manufacturing
- re-configurable manufacturing
- replicable manufacturing

After four minutes of discussion, please use one minute to write up your conclusion. We will provide the timing. Please be bold, there are no right or wrong answers and speculation is part of the process.

Please follow the instructions. Timing will be provided.

How important is “openness” in an RDM scenario, e.g. “open software”, “open standards”, or “open hardware”? How would it be useful if manufacturers and end users could extend 3DP software and hardware?

Next, for each of the seven aspects of RDM, discuss for four minutes whether 3D printing might play a role.

RDM aspect	3DP plays role? (y/n)	Please list in key words how 3D printing might help achieve aspects of RDM:
Localised manufacturing		
Flexible manufacturing		
Resilient manufacturing		
Sustainable manufacturing		
Resource efficient manufacturing		

Re-configurable manufacturing		
Replicable manufacturing		
Any other aspects		

Appendix C: Attended Events

1. ISO STEP-NC Meeting at Baltimore - By attending the ISO standardisation meeting on STEP in Baltimore, we obtained a valuable understanding about the difference between the data transformation during the creation of an artefact based on 3D model data, and the data transformation during the application of the method on an industrial scale. In the latter case, the step of verification becomes very prominent. It seems reasonable to expect that many issues experienced during the creation of the STEP and STEP-NC standards and overall standardisation of CNC could also occur during the standardisation of 3DP and AM. In this context, we would like to note that based on our observations and accounts obtained from practitioners at the meeting, STEP-NC is not able to fully implement a complete MBE (Model Based Engineering) approach, as some practitioners report that the automatic tool path creation is still not feasible, that for anything but simple shapes, tool paths still have to be created manually and specific to the CNC machines, accruing both manual labour and preventing inter-machine portability or machine-independence.

Specifically, there is a discussion within the CNC community whether MBE can be fully realised. What is standing in the way of a full MBE with CNC machines is that currently, after the geometry of a product has been defined, e.g. through computer-aided design (CAD), manual work is still required to define the tool paths, which then have to be transformed into specific instructions for the realising CNC machine. There are three issues here: First, some practitioners feel that the tool paths, i.e. the passes of the milling tools etc. removing material from the block, cannot be calculated by computers and must be defined manually. Second, because capabilities of CNC machines can differ considerably, the passes needed to produce a given artefact may differ considerably between CNC machines. Third, the instruction set also differs between CNC machines so that even for a common set of capabilities, no unified instruction set for all CNC machines exist. This means that the production of a part with CNC manufacturing currently still requires manual intervention in the execution stage, cancelling MBE for CNC manufacturing. Further, because this intervention produces CNC machine-specific output, it prevents the use of the output for different machines.

2. Formnext Industry Fair at Frankfurt - At the inaugural formnext industry fair in Frankfurt, we were able to talk to practitioners and industry representatives with different backgrounds, including innovators improving existing and creating new 3DP technologies and applications, 3DP service providers offering 3DP services and facilities, 3DP machine creators developing and selling 3DP machines, and software developers offering software for 3DP model optimisation and 3D-modelling for 3DP. We also got to meet researchers and representatives of 3DP-related industrial, business and trade representatives. Based on our conversations with practitioners, STL is still the dominant file format for 3DP. STEP is also frequently supported. The 3MF effort was relatively well known but as of yet unsupported except in Windows 10 apparently, whereas the AMF format was not well known and only recognised by few practitioners. Other proprietary formats mentioned by conversation partners were Polyfill, IGES, and OBJ. However, we also encountered device manufacturers who expressed an explicit disregard for any standard effort and prescribed as interfaces g-codes or secondary file formats such as bitmap files to describe layers.

The formnext industry fair further gave us an opportunity to distinguish four different types of industry developing around 3DP: First, there is the 3DP device manufacturer industry. New devices with new printing principles and supporting new printing materials were being demonstrated and promoted. Second, there is a printing material industry, which works as a supplying industry. A currently big topic here appears to be the standardisation of materials. Third, there is the software industry, supplying software for 3DP printing. Two identified subcategories here are developers of 3D modelling software, and of structural optimisation software, i.e. software calculating new geometries for parts to optimise weight-to-strength efficiency. Fourth, there is the 3DP service industry, that is, 3DP machine owners that provide printing services for other companies.

3. Disruptive Innovation Festival - We attended a number of workshops at the Disruptive Innovation Festival (DIF) 2015. DIF hosts events on a wide range of topics on technological innovation and economical changes as online workshops, that is, sessions held over the internet. We attended sessions on 3DP and RDM and gained insights on the socio-technical and economic aspects of RDM and the role 3DP can play here. A major theme at DIF was the maker-aspect in RDM with emphasis on the role 3DP can play in it, i.e. the partial or complete manufacturing of goods at home, individualised for the user.

4. RDM|RSC Network Meeting Exeter - We attended a workshop at the University of Exeter about the role of re-distributed manufacturing for future cities. The sessions at the workshop discussed the technological basics of additive manufacturing as well as the economic foundations of re-distributed manufacturing. A number of scenarios were discussed where re-distributed manufacturing was connected to achieving a circular, sustainable economy. The implications of some of the presentations at the workshop challenged the practicality of the goal of machine-agnosticism in computer-controlled machining, specifically regarding the use of hybrid CNC-AM machines. A dominant theme at the workshop were sociotechnical changes connected to re-distributed manufacturing such as end users hiring or leasing instead of owning products in order to facilitate recycling, or increased product lifetime spans to further manufacturing sustainability. Overall, this workshop enabled us to refine our understanding of RDM into a comprehensive, holistic picture of a scenario combining a number of social and technological advances, and to further understand the theoretical foundations.

5. 3DP-RDM dissemination workshop Cambridge - The Institute for Manufacturing at Cambridge University as the originator of the 3DP-RDM network, of which this research is part, held two events, a coordination event for RDM networks and a 3DP-RDM-specific dissemination event to publish results and ongoing research from the network. At the RDM network coordination event, we were able to conduct a focus group session with two focus groups on where we gathered data from RDM network representatives on their understanding of the role of 3DP in an RDM scenario. At the dissemination event, we presented and discussed our research approach and results from those stages of our research based on literature review, and obtained positive feedback. Further presentations at the event elaborated the emergence of 3DP as a manufacturing method in the context of original expectations and eventual deliveries of previous technological advances.

6. Joint ISO TC261 - ASTM F42 meeting in West Conshohocken - We attended a joint standardisation meeting of ISO and ASTM International for additive manufacturing in West Conshohocken. At this meeting, the ISO TC261 and ASTM F42 groups, both of which are responsible in their respective organisations for developing standards with regards to additive manufacturing, came together to conduct some meetings of their individual standardisation workgroups in a common place and to coordinate their efforts. Of particular interest to us was the meetings of ISO TC261 WG4. This workgroup is responsible for data- and design-related aspects of AM standards, and at this meeting the results of an ad-hoc group comparing the three data standards AMF, STEP and STEP-NC were presented. Further, a liaison from the ISO TC184 group developing STEP-NC introduced the general aims of STEP-NC and first steps of STEP-NC standardisation for AM machines, with an outlook on future collaboration for AM standardisation between TC184 and TC 261 WG4. Other topics discussed at the WG4 meeting were an overview of how far AMF implementation has progressed in the AM industry, and the introduction of design standards. At this meeting, we were also able to present and discuss the preliminary results of the literature-based research. We were further able to recruit additional participants for the empirical part of our study.

7. DSM Seminar at the Brunel University London – The Design for Sustainable Manufacturing (DSM) seminar series is a monthly dissemination event at the Brunel University London. In this seminar series, researchers present to staff and students from the College for Engineering, Physical Sciences and Design as well as the entire university. We presented our research approach, methodology rationale and results in April 2016 to appreciative feedback.

8. Joint ISO TC261 – ASTM F42 meeting in Tokyo – This meeting is the follow-up of the joint ISO-ASTM meeting in West Conshohocken in January 2016, where we will present the study results in the WG4 meeting.