Survey on Additive Manufacturing, Cloud 3D Printing and Services

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Abstract

Cloud Manufacturing (CM) is the concept of using manufacturing resources in a service oriented way over the Internet. Recent developments in Additive Manufacturing (AM) are making it possible to utilise resources ad-hoc as replacement for traditional manufacturing resources in case of spontaneous problems in the established manufacturing processes. In order to be of use in these scenarios the AM resources must adhere to a strict principle of transparency and service composition in adherence to the Cloud Computing (CC) paradigm. With this review we provide an overview over CM, AM and relevant domains as well as present the historical development of scientific research in these fields, starting from 2002. Part of this work is also a meta-review on the domain to further detail its development and structure.

Keywords: Additive Manufacturing; Cloud Manufacturing; 3D Printing Service

1. Introduction

Cloud Manufacturing (here CM, in other works also CMfg) as a concept is not new and has been executed in enterprises for many years [275], under different terms, e.g., Grid Manufacturing [50] or Agile Manufacturing [215].

The decision to have a globally distributed and with many contractors or partners interconnected production process and related supply chains is a luxurious one. Large global corporations and competitions makes “expensive” local production nearly impossible.

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CM is based on a strict service orientation of its constituent production resources and capabilities.

Manufacturing resources become compartmentalised and connected and worked with as service entities, that can be rented, swapped, expanded, dismantled or scaled up or down just by the use of software. This almost instantaneous and flexible model of resource usage is what made the Cloud Computing (CC) paradigm very successful for a number of companies. Here computing resources and data storage are all virtual, living in large data-centres around the globe, with the user only interfacing these resources through well-defined APIs (Application programming interface) and paying for only the resources utilised – apart from the costs inflicted by the cloud service providers due to their business model and the surcharged or otherwise calculated requirement for profit.

With this work we contribute to the dissemination of knowledge in the domain of Additive Manufacturing (AM) and the concept of CM. Cloud Manufacturing can be seen as having two aspects and applications, where the first application is within an industrial environment for which CM provides a concept to embed, connect and utilise existing manufacturing resources, e.g., 3D printers, drilling-, milling- and other machines, i.e., cloud manufacturing is not limited to AM but AM can be utilised within a CM concept. The second application is for end-users that use AM/3D resources over the Internet in lieu acquiring their own 3D printer. The usage in this second application is highly service oriented and has mainly end-users or consumers as target clients. The consumers can profit from online-based services without the requirement of having to own neither hard- nor software resources for 3D printing.

We motivate this work by an overview of the historical development of scientific research in these domains starting from 2002. With this we show that the scientific output within these fields has increased by an average of 41.3 percent annually to about 20000 publications per year (see Sect. 1.2).

To develop a better understanding of the topic at hand we discuss various terminological definitions found in literature and standards. We give critique on the common definitions of AM and propose a simpler, yet more accurate definition.

For the reader to further grasp these domains we study existing journals catering for these communities and discuss reach and inter-connections.

Cloud Manufacturing relies on a service oriented concept of production services or capabilities. We extend an existing study on cloud printing ser-
Cloud manufacturing has two aspects which are detailed in this work. First CM is a methodology that is used within industrial settings for the connection of existing resources to form either a virtual assembly line or to acquire access to manufacturing resources in a service oriented manner. Due to the globalisation of the industry, manufacturers face increased challenges with shorter time-to-markets, requirements for mass customisation (MC) and increased involvement of customers within the product development process. In order to stay or become competitive, companies must utilise their resources more efficiently and where not available they must acquire those resources in an efficient and transparent way. These resources must then be integrated into the existing process environment and released when no longer required.

The concepts of cloud computing, where resources are available as services from providers that can be leased, rented, acquired or utilised in other ways are proposed to be applied to the domain of manufacturing.

Resources like machines and software, as well as capabilities/abilities become transparently available as services that customers or end-users can use through the respective providers and pay for only the services they require momentarily. Most often, no contractual obligations between the provider and the consumer exists (but it can exist, especially for high-value or high-volume usage) which gives the consumer great flexibility at the expense of possible unavailability of resources by the provider.

In the end-user segment, or the consumer aspect of CM the user is interested in using AM resources like 3D printers through a web-based interface in order to be able to have objects produced that are designed to be 3D printed without the necessity to purchase and own a 3D printer themselves. The user commonly uses such services in a similar fashion that they would use a (online) photography lab / printing service. The users’ experience and knowledge of AM and 3D printing can vary significantly.

Albeit these two aspects seem to be far apart, the commonality between them is, that the service operator must provide AM resources in both cases in a transparent and usable manner. Resources must be provided with clear definitions of the interface to the service, i.e., the data consumed by the service and data rendered by the service. The description and provisioning of the service must be hardware agnostic as the consumer must be able to select the resources required, e.g., have an object manufactured either on a FDM (Fused Deposition Modeling, also Fused Filament Fabrication FFF) machine or and SLA (Stereolithography) machine without the necessity to
alter the underlying data and models but by selection.

This work is structured as follows: Section 1.1 provides information of the objective we accomplish with this review. Section 1.1.1 presents the research methodology applied for this work. In section 1.1.2 we disseminate the sources that were used to gather information for this work. Section 1.2 provides a dissemination of the scientific research in these fields with a discussion on its historical development. Chapter 2 contains sections on key terminology and their definition throughout literature and standards. We present these terms as well as synonyms and provide an alternative definition as a proposal. The Chapter 3 is an exhaustive collection of scientific journals relevant to the domains discussed in this work. We provide an insight in their interconnectedness and their structure. Chapter 4 provides a meta-review on the subject for the reader to get a further reaching understanding of the subject and its relevant components.

In Chapter 4.1 we discuss the audience or target group for CM and 3D printing related cloud services. Chapter 5 extends the study by Rayna and Striukova [204] due to the importance of 3D printing related cloud services for the topic at hand. Section 6 provides the information on the concepts, terminology, methods relevant to the subject as they are disseminated in literature. We conclude this work with a summary in Chapter 7.

1.1. Research Objective

This review is performed to establish an overview on the concept and implementation of CM and the utilisation of Additive Manufacturing (AM) therein. For the understanding it is required to become familiar with the various definitions available and the problems arising from inconsistent usage of terminology. For this we compile differing definitions on key terminology.

With this work we aim to present an overview over the topic of CM, and its current research findings. We furthermore present a summary overview over existing online and cloud based 3D printing services that can either be regarded as implementations of CM or be utilised in CM scenarios. This part is to extend the knowledge on relevant online services and their orientation towards numerous services. With the presentation of the identified journals that cater for AM, DM, RP, RM and 3D printing research we want to provide other researchers with insight into possible publication venues and a starting point for the identification of relevant sources for their own work. The review work of this article has the objective to identify relevant literature and summarise the key and essential findings thereof. The review also is intended to
provide a high level overview on identified research needs that are considered essential for the evolution of AM and CM.

1.1.1. Methodology

The first part of this review is the analysis of other reviews in order to establish a foundation of the existing works and to have a baseline for the analysis of the journals catering to this domain.

The journals are identified and presented in order to help researchers in finding a suitable publication venue and to present the recent development in this area. The journals are identified by literature research, web searching (see Sect. 1.1.2), and as a result of the review analysis.

This review identified its sources by web search for each of the identified topics depicted in the concept map (See Sect. 6.1), where the first 30 results from the search engines (see Sect. 1.1.2) each are scanned first by title, then by their abstract. For the creation of the topological map an iterative process is applied. The process starts with the analysis of the following works \[273, 265, 275, 279, 102\] which we had prior knowledge of due to previous engagements in this research area. After the analysis a backward- and forward search is performed.
The searches for the content of the review are sorted by relevance, according to the search engine operator. The articles are then analysed and its core concepts are presented in this work.

The reviews for the meta-review are identified by a web search and data gathered during our review.

For the compilation of the definitions an extraction process is employed where the identified literature for the review is basis for information extraction and dissemination. The compilation is expanded by literature and Internet research for the appropriate keywords and concepts.

The extension to the study by Rayna and Striukova [204] is performed following the research methodology applied in the original work.

1.1.2. Sources
This review is based on scientific literature acquired through the respective publishers and searched for using the following search engines:

- Google Scholar
- SemanticScholar
- dblp
- Web of Science
- ProQuest

Microsoft Academic Search is not used for the search as the quality and number of results is unsatisfactory. Scopus is not used for the research, as we have no subscription for it. The search engines differ in the handling of grouping and selection operators (e.g., OR, +). For each search engine the appropriate operators where selected when not explicitly stated otherwise. As a search engine for scientific literature, Google Scholar, yields the most
results but with a high degree of unrelated or otherwise unusable sources, like the Google search engine itself. Furthermore, the search engine enforces strict usage rules thus hindering automated querying and usage. Results from patents and citations are excluded from the result set for Google Scholar.

Semantic Scholar offers a responsive interface, that allows for automated querying through JSON to “millions” of articles from computer science - a statement that we can not verify as we have seen articles from other domains too. The dblp project indexes over 3333333 from computer science in a very high quality. Its interface allows for automated and scripted usage. Web of Science provides an index of a large number (over 56 millions) of scientific works. The entries in the index are of high quality but the interface is rather restrictive. ProQuest also has a very restrictive and non-scriptable interface and contains over 54 million entries in its corpus, among which are historical news articles and dissertations. The quality of the results is high. ProQuest and Web of Science are subscription based services.

1.2. Development in Scientific Publications

The significance and maturity of a research area is reflected in the number of publications available. We perform a keyword based analysis utilising the sources described in Section 1.1.2. The searches are performed with a number of relevant keywords (including various technologies and methods for AM) and a restriction of the time period starting from 2002 to 2016. The queries are also restricted on the type of results with an exclusion to citations and patents, where applicable. For a study on the patents and the development of patent registrations for this domain we refer to Park et al. [190].

Caveat: Searching on search engines for specific keywords like clip and lens in their abbreviated form will lead to a number of skewed results from works that are not significant for this body of work. For example the search for “Additive Manufacturing” and LENS yield articles in the results that

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8 https://google.com
9 JavaScript Object Notation
10 https://www.semanticscholar.org/faq#index-size
11 News from 2016-05-03: “Today, dblp reached the wonderful "Schnapszahl" of 3,333,333 publications”
12 A search for publications with its publication date between 1700 and 2100 yields 56998216 results
13 A search for publications with its publication date after 1700 yields 54266680 results
are either fabricating (optical) lenses using AM or are about lenses in lasers that are used in AM. In case the result sets are as large as in our case it is not feasible to remove those erroneous results and adjust the result set accordingly. We make the reader aware to only take the given numbers as an indication.

In Fig. 2 to Fig. 7 the classification of scientific articles according to Web of Science is shown. The classifications do not add up to 100 percent as the respective articles can be classified in more than one field. In the figures the number of results per search term is also listed. Domains with less than five percent aggregated classification are grouped together as “OTHER”.

In Fig. 8 the accumulated prevalence of the terms 3D printing versus Additive Manufacturing (AM) is displayed. For these numbers queries are made for a combination of search terms and restrictions on the time period. The scale of the Y-Axis is logarithmic due to the large differences in the number of results per search engine. The dblp database returned the lowest number
Figure 4: Classification of articles for 3D Printing; source of data: webofknowledge.com

Figure 5: Classification of articles for Rapid Manufacturing; source of data: webofknowledge.com

Figure 6: Classification of articles for Rapid Prototyping; source of data: webofknowledge.com
of results with results consistently less than 10. Google Scholar yielded the largest number of results with the accumulated number of results for the term AM gaining on the term 3D printing since 2009. In Fig. 9 the prevalence of certain AM or 3D Printing technologies is studied by the number of articles from four different search engines for the respective combination of search terms. The largest number of results are from Google Scholar for search term combinations with “3D Printing”. Furthermore, a generalised search is performed for the terminology “Laser, Lithography and Powder”, e.g., summarising technologies like SLM (Selective Laser Melting), SLS (Selective Laser Sintering), SLA, LOM (Laminated Object Manufacturing), LENS (Laser Engineered Net Shaping) for the term “Laser”. The search for technologies like CLIP and LENS are problematic due to the non-specificity of the terminology as described before (See note 1.2).

2. Definition and Terminology

In general the usage of the terminology within this field is very inconsistent. Commonly and colloquially the terms 3D printing and AM are used as synonyms. Analysing the prevalence of either of these terms we find that 3D printing is slightly more prevalent for results of scientific literature with 68164 results for the sources described in Sect. 1.1.2 during the period of 2002–2016. In the same period there are over 59506 results for the term Additive Manufacturing. Semantic Scholar provided significantly more results (7072 over 1211) for 3D printing and Web of Science yielded almost four times the number of results for Additive Manufacturing over 3D Printing (1956 results to 578). There is also no clear trend in the usage of either terms. With this section we exemplify this situation and present
Comparison of AM and 3D printing over 4 search engines

source of data: scholar.google.com, semanticscholar.org, dblp.uni-trier.de, webofknowledge.com, progquest.com

Figure 8: Comparison of AM and 3D Printing on selected search engines (2002–2016)
Figure 9: Comparison of 3D printing technologies on selected search engines (2002–2016)
common definitions throughout literature and standards. We furthermore add our point of view in the form of a critique at the end of the section.

2.1. Additive Manufacturing and 3D Printing

In this section we present established definitions for AM and related terminology as presented in literature and standards.

2.1.1. Definitions of Additive Manufacturing

AM is most often regarded as an umbrella term for technology and methods for the creation of objects from digital models from scratch. It is usually in contrast to subtractive and formative methods of manufacturing as defined in the standard [1]. It is also commonly a synonym for 3D printing.

Gibson et al. [89] define AM as: “Additive manufacturing is the formalised term for what used to be called rapid prototyping and what is popularly called 3D Printing. [...] Referred to in short as AM, the basic principle of this technology is that a model, initially generated using a three-dimensional Computer-Aided Design (3D CAD) system, can be fabricated directly without the need for process planning. [...]”

Gebhardt [88] defines AM as: “Als Generative Fertigungsverfahren werden alle Fertigungsverfahren bezeichnet, die Bauteile durch Auf- oder Aneinanderfügen von Volumenelementen (Voxel’n), vorzugsweise schichtweise, automatisiert herstellen.”, which we translate as “As generative/additive manufacturing processes all production processes are referred that produce components automatically by depositioning of volume elements (Voxels), preferably layer-wise”.

The VDI directives VDI 3404 (Version 2009 [4] and 2014 [6]) define additive fabrication as: “Additive fabrication refers to manufacturing processes which employ an additive technique whereby successive layers or units are built up to form a model.”.

The 2009 directive “VDI-Richtlinie: VDI 3404 Generative Fertigungsverfahren - Rapid-Technologien (Rapid Prototyping) - Grundlagen, Begriffe, Qualitätskenngrößen, Liefervereinbarungen” and the 2014 directive “VDI-Richtlinie: VDI 3404 Additive Fertigung - Grundlagen, Begriffe, Verfahrensbeschreibungen” are both currently in retracted states.

The also retracted ASTM standard F2792-12a “Standard terminology for additive manufacturing technologies” defines AM as “A process of joining materials to make objects from 3D model data, usually layer upon layer,
as opposed to subtractive manufacturing methodologies.” with the following synonyms listed “additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.”.

Bechthold et al. [26] define AM as: “The terms additive manufacturing (AM) and 3D printing describe production processes in which a solid 3D structure is produced layer by layer by the deposition of suitable materials via an additive manufacturing machine.”

Thomas and Gilbert [242] define AM as: “Additive manufacturing is the process of joining materials to make objects from three-dimensional (3D) models layer by layer as opposed to subtractive methods that remove material. The terms additive manufacturing and 3D printing tend to be used interchangeably to describe the same approach to fabricating parts. This technology is used to produce models, prototypes, patterns, components, and parts using a variety of materials including plastic, metal, ceramics, glass, and composites”

Klocke [136] defines AM as: “Generative Verfahren: Diese Verfahrensgruppe umfasst alle Technologien, mit denen eine aufbauende, schichtweise Fertigung von Bauteilen realisiert wird. Sie werden auch als Additive Manufacturing Technologies oder als Layer based Manufacturing Technologies bezeichnet. Zum Herstellen der Schichten wird häufig Laserstrahlung verwendet. [...]”

translation “Generative Processes: This process group contains all technologies, with which an additive, layer-wise generation of parts is realised. They are also referred to as additive manufacturing technologies or layer based manufacturing technologies. For the creation of the layers oftentimes laser emission is used. [...]”

In the ASTM F2792-12a [5] standard AM is defined as: “process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.”

Gao et al. [83] use the term AM and 3D printing synonymously: “Additive manufacturing (AM), also referred to as 3D printing, [...].”

Sames et al. [214] also use the term AM and 3D printing synonymously: “Additive manufacturing (AM), also known as three-dimensional (3D) printing, [...].”

Lachmayer and Lippert [140] define AM as: “Das Additive Manufacturing
Additive manufacturing as an umbrella term for Rapid Prototyping (RP), Rapid Tooling (RT), Direct Manufacturing (DM) and Rapid Repair (RR) is based on the principle of the additive layer fabrication in x-, y- and z-direction for the fabrication of a (near-) net-shape geometry by machines.

The ISO/ASTM Standard 52900:2015(E) [9] defines AM as: “process of joining materials to make parts (2.6.1) from 3D model data, usually layer (2.3.10) upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies”.

2.1.2. Definitions of 3D Printing

According to Gebhardt [88] 3D Printing is a generic term that is synonymous to AM and is replacing the term AM in the future due to its simplicity. Bechtholdt et al. [26] use the terms 3D Printing and AM synonymously as umbrella terms for technologies and applications. In the VDI directive [7] the term 3D printing is used for a certain additive process but it is acknowledged that it is generally used as a synonym for AM.

The ASTM standard F2792-12a (retracted) defines 3D printing as “The fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology.” but also acknowledges the common synonymous use of this term for AM, mostly of low-end quality and price machines.

Gibson [89] uses the term 3D Printing for the technology invented by researchers at MIT [212] but also acknowledges that it is used synonymously for AM and will eventually replace the term AM due to media coverage.

The ISO/ASTM Standard 52900:2015(E) [9] defines 3D Printing as: “fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology”.

It is also noted in this standard that the term 3D printing is often used as a synonym for AM, mostly in non-technical context. Furthermore, it is noted that 3D printing is associated with low price and capability machines.

2.1.3. Definitions of Rapid Prototyping

In Hopkinson and Dickens [106] Rapid Prototyping (RP) is defined as: “RP refers to a group of commercially available processes which are used to
create solid 3D parts from CAD, from this point onwards these processes will be referred to as layer manufacturing techniques (LMTs)

The VDI directive 3405 defines RP as: “Additive fabrication of parts with limited functionality, but with sufficiently well-defined specific characteristics.”

Weber et al. [267] define RP as: “Early AM parts were created for the rapid prototyping market and were first employed as visual aids and presentation models. Many lower cost AM systems are still used in this way.”

2.1.4. Definitions of Rapid Manufacturing

Hopkinson et al. [108] define Rapid Manufacturing (RM) as: “the use of a computer aided design (CAD)-based automated additive manufacturing process to construct that are used directly as finished products or components.”

Previously Hopkinson and Dickens [106] defined RM as: “Rapid manufacturing uses LMTs for the direct manufacture of solid 3D products to be used by the end user either as parts of assemblies or as stand-alone products.”

The VDI directive 3404 Version 2009 [4] defines RM as: “Additive fabrication of end products (often also described as production parts). Characteristics: Has all the characteristics of the end product or is accepted by the customer for “series production readiness”. Material is identical to that of the end product. Construction corresponds to that of the end product.”

The VDI directive 3405 [7] defines RM as a synonym for direct manufacturing, which is defined as: “Additive fabrication of end products.”

2.1.5. Definitions of Rapid Tooling

King and Tansey [135] define Rapid Tooling (RT) as an extension of RP as such: “Rapid tooling is a progression from rapid prototyping. It is the ability to build prototype tools directly as opposed to prototype products directly from the CAD model resulting in compressed time to market solutions.”

The VDI directive 3405 [7] defines RT as: “The use of additive technologies and processes to fabricate end products which are used as tools, moulds and mould inserts.”

Weber et al. [267] define RT as: “Another class of applications for AM parts is patterns for tooling or tooling directly made by AM. AM processes can be used to significantly shorten tooling time and are especially useful for low-run production of products.”
2.1.6. Definitions of Cloud Manufacturing

The work by Li et al. [112] appears to be the first to introduce the concept and definition of Cloud Manufacturing (CM), but unfortunately this article is only available in Chinese and could therefore not be considered. The article is cited by more than 450 publications according to Google Scholar.

Wu and Yang [280] define CM as such: “Cloud manufacturing is an integrated supporting environment both for the share and integration of resources in enterprise. It provides virtual manufacturing resources pools, which shields the heterogeneousness and the regional distribution of resources by the way of virtualisation. Cloud manufacturing provides a cooperative work environment for manufacturing enterprises and individuals and enables the cooperation of enterprise.”

Tao et al. [237] define CM indirectly by the following description: “Cloud manufacturing is a computing and service-oriented manufacturing model developed from existing advanced manufacturing models (e.g., ASP, AM, NM, MGrid) and enterprise information technologies under the support of cloud computing, IoT, virtualisation and service-oriented technologies, and advanced computing technologies”

Xu [283] defines CM similar to the NIST definition of CC as: “a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable manufacturing resources (e.g., manufacturing software tools, manufacturing equipment, and manufacturing capabilities) that can be rapidly provisioned and released with minimal management effort or service provider interaction”. This definition is also used in the work by Wang and Xu [266].

Zhang et al. [297] describe CM as: “Cloud manufacturing (CMfg) is a new manufacturing paradigm based on networks. It uses the network, cloud computing, service computing and manufacturing enabling technologies to transform manufacturing resources and manufacturing capabilities into manufacturing services, which can be managed and operated in an intelligent and unified way to enable the full sharing and circulating of manufacturing resources and manufacturing capabilities. CMfg can provide safe, reliable, high-quality, cheap and on-demand manufacturing services for the whole life cycle of manufacturing.”

2.1.7. Synonyms for AM

As with the previous definitions for AM, RP, RT, RM and 3D printing there is no consensus in the terminology for synonyms of AM in general. The
following synonyms can be found in literature and are used in existing works.

- direct layer manufacturing or layer manufacturing or additive layer manufacturing
- direct digital manufacturing is a synonym for rapid manufacturing
- solid freeform fabrication (SFF), three dimensional printing
- 3D printing, Additive Techniques, Layer Manufacturing, and Freeform fabrication
- additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication
- “The technical name for 3D printing is additive manufacturing [...]”

2.1.8. Critique

The existing definitions fall short on their focus on the layer-wise creation of objects as technologies like LENS and multi-axis \( (n > 3) \) are not bound and defined by a layer structure but can regarded as a form of AM as they create objects based on 3D (CAD) models from scratch without any of the characteristics of traditional subtractive or formative fabrication methods.

Through a systematic decomposition of the existing definitions of AM we conclude that the basic commonality of AM is described as the creation of a physical object from a digital model by a machine.

Furthermore, we propose the term AM as an umbrella term that signifies industrial, commercial or professional application and usage whereas 3D printing can be colloquially used for technologies and methods for the creation of physical objects from 3D (CAD) models in other situations.

For the actual building machines of additively manufactured parts we recommend the synonymous use of AM fabricator or 3D printer. The first as it describes the functionality in a precise way and the second as it is commonly used and understood by a broad audience.

\(^{14}\) Also [https://wohlersassociates.com/additive-manufacturing.html](https://wohlersassociates.com/additive-manufacturing.html)
3. Journals related to the Subject

We have identified a number of journals specialising in the domain of AM. In this section we explain their foci and their scientific scope.

The following journals cater partially or solely for the academic dissemination of works based in or related to the domains of AM, RM, RP and 3D Printing. These journals are identified using the service of the Directory of Open Access Journals\(^{15}\) Thomson Reuters Web of Science\(^{16}\) and the articles used for this review. Only journals with indication for AM, RM, RP or 3D Printing in either the title or the scope are listed below.

In the following overview the abbreviations EiC for Editor in Chief, ImpactF for Impact Factor and SJR for SCImago Journal Rank Indicator\(^{17}\) are used. The Impact Factor is either acquired from the journal’s home page directly when available or looked up from Thomson Reuters InCites Journal Citation Reports\(^{18}\). For a number of journals neither a SJR nor the IF could be found. The numbers for the available volumes, issues and articles are directly extracted from the respective journal’s website. The listing contains a full list of all members of the board and editors per journal for an assessment of the interconnection between the various journals. Editors and members of the board that are involved in more than one journal are indicated by italicised text and the indication in which other journal they are involved. The journals are ordered by their number of articles published and if two or more journals have an equal number of publications the ordering is chronological. The journals without publications and age available are sorted by their ISSN.

The 20 journals have an accumulated 22616 articles published (respectively 17877 articles, when only considering articles from Journal 2 after it was renamed). The median of the first publication date is 2014. Under the assumption that the articles are published equally since the first Journal (Journal 1) started in 1985, 31 years ago, this results in an average number of 576 articles per year, which accounts for approximately 18 % of the average accumulated results of 3197 scientific works indexed by

\(^{15}\)https://doaj.org
\(^{16}\)http://webofknowledge.com
\(^{17}\)“It expresses the average number of weighted citations received in the selected year by the documents published in the selected journal in the three previous years”, see http://www.scimagojr.com/SCImagoJournalRank.pdf for more details
\(^{18}\)https://jcr.incites.thomsonreuters.com
http://scholar.google.com for the time frame of 2002 to 2016 (See also Section 1.1). The information on the journals is accurate as of 2016-08-10 according to the respective websites.

1. The International Journal of Advanced Manufacturing Technology

   Publisher Springer
   ISSN 1433-3015
   URL http://www.springer.com/engineering/production+engineering/journal/170/PSE
   ImpactF 1.568
   H-Index 71
   SJR 0.91
   Since 1985
   Volumes 85
   Issues 432
   Articles 11727
   EiC Andrew Y. C. Nee (See also Journal 3)
   Board and Editors 1) Kai Cheng 2) David W. Russell 3) M. S. Shunmugam 4) Erhan Budak 5) D. Ben-Arieh 6) C. Brecher 7) H. van Brussel 8) B. Çatay 9) F. T. S. Chan (See also Journal 3) 10) F. F. Chen 11) G. Chryssolouris 12) Chee Kai Chua (See also Journals 4, 6, 11) 13) M. Combacau 14) A. Crosnier 15) S. S. Dimov 16) L. Fratini 17) M. W. Fu 18) H. Huang 19) V. K. Jain 20) M. K. Jeong 21) P. Ji 22) W.-Y. Jywe 23) R. T. Kumara 24) A. Kusiak 25) B. Lauwers 26) W. B. Lee 27) C. R. Nagarajah 28) E. Niemi 29) D. T. Pham 30) S. G. Ponnambalam 31) M. M. Ratnam 32) V. R. Rao 33) C. Saygin 34) W. Steen 35) D. J. Stephenson 36) M. K. Tiwari (See also Journal 18) 37) E. Vezzetti 38) G. Vosniakos 39) X. Xu (See also Journal 3) 40) Y. X. Yao 41) A. R. Yildiz 42) M. Zoe (See also Journals 7, 12) 43) H.-C. Zhang 44) L. Zhang 45) A.G. Mamalis

2. Journal of Manufacturing Science and Engineering

   Publisher The American Society of Mechanical Engineers

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19 http://www.scimagojr.com/journalsearch.php?q=20428&tip=sid&clean=0
20 http://www.scimagojr.com/journalsearch.php?q=20428&tip=sid&clean=0
ISSN 1087-1357
URL http://manufacturingscience.asmedigitalcollection.asme.org/journal.aspx
ImpactF 1.087
H-Index 68
SJR 0.8
Since 1996
Volumes 138
Issues 101 (Since “Journal of Engineering for Industry” was renamed to its current title)
Articles 7066 (2327 since the renaming in May 1996)
EiC Y. Lawrence Yao
Board and Editors 1) Sam Anand 2) Wayne Cai (See also Journal 3) Jaime Camello 4) Hongqiang Chen 5) Dragan Djurdjanovic 6) Guillaume Fromentin 7) Yuebin Guo 8) Yong Huang (See also Journal 9) Yannis Korkolis 10) Laine Mears 11) Gracious Ngaile (See also Journal 12) Radu Pavel 13) Zhijian Pei 14) Xiaoping Qian 15) Tony Schmitz 16) Jianjun (Jan) Shi 17) Daniel Walczyk 18) Donggang Yao 19) Allen Y. Yi

3. Robotics and Computer-Integrated Manufacturing

Publisher Elsevier B.V.
ISSN 0736-5845
URL http://www.journals.elsevier.com/robotics-and-computer-integrated-manufacturing
ImpactF 2.077
H-Index 61
SJR 1.61
Since 1984–1994, 1996 ongoing
Volumes 44
Issues 145
Articles 2191
EiC Andre Sharon
Board and Editors 1) M. Haegele 2) L. Wang 3) M. M. Ahmad 4) K.
Akella 5) H. Asada 6) J. Baillieul 7) T. Binford 8) D. Bossi 9) T. Broughton 10) M. Caramanis 11) F. T. S. Chan (See also Journal 1) 12) G. Chryssolouris 13) J. Deasley 14) S. Dubowsky 15) E. Eloranta 16) K. C. Fan 17) J. Y. H. Fuh (See also Journals 4, 18) J. X. Gao 19) M. Gevelber 20) Y. Ito 21) K. Iwata 22) T. Kanade 23) F. Liu 24) L. Luong 25) K. L. Mak 26) K. McKay 27) A. Meng 28) N. Nagel 29) A. Y. C. Nee (See also Journal 1) 30) G. Reinhardt 31) R. D. Schraft 32) W. P. Seering 33) D. Spath 34) H. C. G. Spur 35) N. Suh 36) M. K. Tiwari 37) H. Van Brussel 38) F. B. Vernadat 39) A. Villa 40) M. Weck 41) H. Worn 42) K. Wright 43) C. Wu 44) X. Xu (See also Journal 1)

4. Rapid Prototyping Journal
Publisher Emerald Group Publishing, Ltd
ISSN 1355-2546
URL http://www.emeraldinsight.com/loi/rpj
ImpactF 1.352
H-Index 49
SJR 0.81
Since 1995
Volumes 22
Issues 113
Articles 882
EiC Ian Campbell
Board and Editors 1) David Bourell (See also Journals 10, 6) 2) Ian Gibson (See also Journals 8, 6) 3) James Martin 4) Sung-Hoon Ahn 5) Paulo Jorge da Silva Bártilo (See also Journals 17, 6) 6) Deon de Beer 7) Alain Bernard (See also Journals 13, 8, 6) 8) Richard Bibb (See also Journal 11) 9) U. Chandrasekhar 10) Khershed Cooper (See also Journal 10) 11) Denis Cormier (See also Journals 9, 8) 12) Henrique de Amorim Almeida (See also Journal 12) 13) Phill Dickens 14) Olaf Diegel (See also Journal 10) 15) Jerry Fuh (See also Journals 15, 3) 16) Jorge Ramos Grez 17) Chua Chee Kāi (See also Journals 1, 6, 11) 18) Jean-Pierre

http://www.scimagojr.com/journalsearch.php?q=21691&tip=sid&clean=0
http://www.scimagojr.com/journalsearch.php?q=21691&tip=sid&clean=0
5. Journal of Manufacturing Processes

Publisher Elsevier B.V.
ISSN 1526-6125
URL http://www.journals.elsevier.com/journal-of-manufacturing-processes
ImpactF 1.771
H-Index 24
SJR 1.0928
Since 1999
Volumes 24
Issues 47
Articles 620
EiC Shiv G. Kapoor
Board and Editors 1) M. Annoni 2) W. Cai (See also Journal 2) 3) G. Cheng 4) J. Dong 5) Z. Feng 6) G. Y. Kim 7) A. S. Kumar 8) X. Li 9) G. Ngaile (See also Journal 2) 10) S. S. Park 11) M. Sundaram 12) B. Wu 13) H. Yamaguchi Greenslet 14) Y. Zhang

6. Virtual and Physical Prototyping

Publisher Taylor & Francis
ISSN 1745-2767
URL http://www.tandfonline.com/loi/nvpp20
ImpactF N/A
H-Index 1529
SJR 0.4230
Since 2006
Volumes 11
Issues 42
Articles 294
EiC Paulo Jorge da Silva Bártolo (See also Journals [4, 17, 11]), Chee Kai Chua (See also Journals [1, 4, 11])

Board and Editors 1) Wai Yee Yeong (See also Journal [11] 2) Alain Bernard (See also Journals [4, 13, 8] 3) Anath Fischer (See also Journal [12] 4) Bopaya Bidanda 5) Cijun Shuai (See also Journal [11] 6) David Bourell (See also Journals [10, 4] 7) David Dean (See also Journal [12] 8) Dongjin Yoo (See also Journal [11] 9) Jack Zhou 10) Ian Gibson (See also Journals [4, 8] 11) Jiankang He (See also Journal [11] 12) John Lewandowski 13) Martin Dunn 14) Ming Leu 15) Feifeng Li 16) Shoufeng Yang (See also Journals [17, 11] 17) Shlomo Magdassi 18) Yong Chen (See also Journal [8])

7. RT ejournal

Publisher University Library of the FH-Aachen University of applied Science
ISSN 1614-0923
URL http://www.rtejournal.de
ImpactF N/A
H-Index N/A
SJR N/A
Since 2004
Volumes 13
Issues 13
Articles 155
EiC Andreas Gebhardt

Board and Editors 1) Ralf Eckhard Beyer 2) Dietmar Drummer 3) Karl-Heinrich Grote 4) Sabine Sändig 5) Gerd Witt (See also Journal [12] 6) Michael Zäh (See also Journals [1, 12])

8. International Journal of Rapid Manufacturing

Publisher Inderscience Enterprises Ltd.
ISSN 1757-8825
URL http://www.inderscience.com/ijrapidm
ImpactF N/A
9. Additive Manufacturing

Publisher Elsevier B.V.
ISSN 2214-8604
URL http://www.journals.elsevier.com/additive-manufacturing

ImpactF N/A
H-Index 3
SJR 1.04
Since 2014
Volumes N/A
Issues 12
Articles 93

EiC Ryan Wicker

Board and Editors 1) E. MacDonald 2) M. Perez 3) A. Bandyopadhyay 4) J. Beaman (See also Journal 8) 5) J. Beuth 6) S. Bose 7) S. Chen 8) J. W Choi 9) K. Chou 10) D. Cormier (See also Journals 4, 8) 11) K. Creehan 12) C. Elkins 13) S. Fish 14) D. D. Gu 15) O. Harrysson 16) D. Hofmann 17) N. Hopkinson 18) Y. Huang (See also Journal 2) 19) K. Jurrens 20) K. F. Leong 21) J. Lewis (See also Journal 10) 22) L. Love 23) R. Martukanitz 24) D. Mei 25) R. Resnick (See also Journal 10) 26) D. Rosen (See also Journals 4, 10) 27) C. Spadaccini 28) B. Stucker (See also Journals 10, 4) 29) C. Tuck 30) C. Williams

10. 3D Printing and Additive Manufacturing

Publisher Mary Ann Liebert, Inc
ISSN 2329-7662
URL http://www.liebertpub.com/overview/3d-printing-and-additive-manufacturing

ImpactF N/A
H-Index N/A
SJR N/A
Since 2014
Volumes 3
Issues 10
Articles 86

EiC Skylar Tibbits

Board and Editors 1) Hod Lipson 2) Craig Ryan 3) Anthony Atala 4) David Benjamin 5) Lawrence J. Bonassar 6) David Bourell (See also Journals 4, 6) 7) Adrian Bowyer 8) Glen Bull 9) Adam Cohen 10) Khershed P. Cooper (See also Journal 4) 11) Scott Crump 12) Olaf Diegel (See also Journal 4) 13) Richard Hague 14) John F. Hornick 15) Weidong Huang 16) Takeo Igarashi 17) Bryan Kelly 18) Behrokh Khoshnevis (See also Journal 8) 19) Matthias Kohler 20) L. Jyothish Kumar (See also Journals 13, 8) 21) Melba Kurman 22) Jennifer A. Lewis (See also Journal 9) 23) Jos Malda 24) Gonzalo Martinez 25) Neri Oxman 26) Bre Pettis 27) Sharon Collins Presnell 28) Phil Reeves 29) Avi N. Reichental 30) Ralph Resnick (See also Journal 9) 31) David W. Rosen (See also Jour-
11. International Journal of Bioprinting
Publisher Whioce Publishing Pte Ltd
ISSN 2424-8002
URL http://ijb.whioce.com/index.php/int-j-bioprinting
ImpactF N/A
H-Index N/A
SJR N/A
Since 2015
Volumes 2
Issues 3
Articles 31
EiC Chee Kai Chua (See also Journals 1, 4, 6)
Board and Editors 1) Wai Yee Yeong (See also Journal 6) 2) Aleksandr Ovsianikov (See also Journal 17) 3) Ali Khademhosseini (See also Journal 15) 4) Boris N. Chichkov (See also Journal 17) 5) Charlotte Hauser 6) Cijun Shuai (See also Journal 6) 7) Dong Jin Yoo (See also Journal 6) 8) Frederik Claeysens 9) Geun Hyung Kim 10) Giovanni Vozzi (See also Journals 17, 15) 11) Ibrahim Tarik Ozbolat 12) Jiankang He (See also Journal 6) 13) Lay Poh Tan 14) Makoto Nakamura 15) Martin Birchall 16) Paulo Jorge Da Silva Bartolo (See also Journals 17, 18) 17) Peter Dubrue1 18) Richard Bibb (See also Journal 4) 19) Roger Narayan (See also Journals 20, 15) 20) Savas Tasoglu (See also Journals 17, 15) 21) Shoufeng Yang (See also Journals 6, 17) 22) Vladimir Mironov 23) Xiaohong Wang 24) Jia An

12. Progress in Additive Manufacturing
Publisher Springer
ISSN 2363-9520
URL http://www.springer.com/engineering/production+engineering/journal/40964
ImpactF N/A
H-Index N/A
13. International Journal on Additive Manufacturing Technologies

Publisher Additive Manufacturing Society of India
ISSN 2395-4221
URL [http://amsi.org.in/homejournal.html](http://amsi.org.in/homejournal.html)
ImpactF N/A
H-Index N/A
SJR N/A
Since 2015
Volumes 1
Issues 1
Articles 7
EiC Pulak M. Pandey (See also Journal 8), David Ian Wimpenny, Ravi Kumar Dwivedi
Board and Editors 1) L. Jyothish Kumar (See also Journals 10, 8) 2) Keshavamurthy D. B. 3) Khalid Abdelghany 4) Suman Das 5) Alain Bernard (See also Journals 4, 8, 6) 6) C. S. Kumar 7) Bahram Asiabanpour (See also Journal 8) 8) K. P. Raju Rajurkar 9) Ehsan Toyskerki 10) Wan Abdul Rahman 11) Sarat Singamneni 12) Vijayavel Bagavath Singh

14. 3D Printing in Medicine

Publisher Springer
ISSN 2365-6271
URL [http://www.springer.com/medicine/radiology/journal/41205](http://www.springer.com/medicine/radiology/journal/41205)
ImpactF N/A
H-Index N/A
SJR N/A
Since 2015
Volumes 2
Issues 4
Articles 3
EiC Frank J. Rybicki
Board and Editors 1) Leonid L. Chepelev 2) Andy Christensen 3) Koen Engelborghs 4) Andreas Giannopoulos 5) Gerald T. Grant 6) Ciprian N. Ionita 7) Peter Liacouras 8) Jane M. Matsumoto 9) Dimitrios Mitsouras 10) Jonathan M. Morris 11) R. Scott Rader 12) Adnan Sheikh 13) Carlos Torres 14) Shi-Joon Yoo 15) Nicole Wake 16) William Weadock

15. Bioprinting
Publisher Elsevier B.V.
ISSN 2405-8866
URL http://www.journals.elsevier.com/bioprinting
ImpactF N/A
H-Index N/A
SJR N/A
Since 2016
Volumes 1
Issues N/A
Articles 1
EiC A. Atala
Board and Editors 1) S. V. Murphy 2) T. Boland 3) P. Campbell 4) U. Demirci (See also Journal 17) 5) B. Doyle 6) J. Fisher 7) J. Y. H. Fuh (See also Journals 4 3 8) A. K. Gaharwar 9) P. Gatenhorn 10) K. Jakab 11) J. Jessop 12) A. Khademhosseini (See also Journal 13) 13) S. J. Lee 14) I. Lelkes 15) J. Lim 16) A. G. Mikos 17) R. Narayan (See also Journals 20 11 18) T. Sercombe (See also Journals 4 8 19) A. Skardal 20) S. Tasoglu (See also Journals 21) D. J. Thomas 22) G. Vozzi (See also Journals 17 23) I. Whitaker (See also Journal 17 24) S. K. Williams

16. 3D Printing – Science and Technology
Publisher DE GRUYTER OPEN
ISSN 1896-155X
URL http://www.degruyter.com/view/j/3dpst
ImpactF N/A
H-Index N/A
SJR N/A
Since 2016
Volumes 0
Issues 0
Articles 0
EiC Haim Abramovich
Board and Editors 1) Christopher A. Brown 2) Paolo Fino 3) Amnon Shirizly 4) Frank Walther 5) Kaufui Wong

17. Journal of 3D Printing in Medicine
Publisher Future Medicine Ltd
ISSN 2059-4755
URL http://www.futuremedicine.com/page/journal/3dp/editors.jsp
ImpactF N/A
H-Index N/A
SJR N/A
Since 2016
Volumes 0
Issues 0
Articles 0
EiC Dietmar W Hutmacher
Board and Editors 1) Peter Choong 2) Michael Schuetz 3) Iain S. Whitaker (See also Journal 15) 4) Shoufeng Yang (See also Journals 6, 11) 5) Paulo Jorge Bártolo (See also Journals 4, 6, 11) 6) Luiz E. Bertassoni 7) Faiz Y. Bhora 8) Boris N. Chichkov (See also Journal 11) 9) Utkan Demirci (See also Journal 15) 10) Michael Gelinsky 11) Ruth Goodridge 12) Robert E. Guldberg 13) Scott J. Hollister 14) Zita M. Jessop 15) Jordan S. Miller 16) Adrian Neagu 17) Aleksandr Ovsianikov (See also Journal 11) 18) Katja Schenke-Layland 19) Ralf Schumacher 20) Jorge Vicente Lopes da Silva 21) Chris Sutcliffe 22) Savas Tasoglu (See also Journals 15, 11) 23) Daniel Thomas 24) Martijn van Griensven 25) Giovanni
Vozzi (See also Journals 15, 11) 26) David J. Williams 27) Chris J. Wright 28) Jing Yang 29) Nizar Zein

18. Smart and Sustainable Manufacturing Systems
   Publisher ASTM
   ISSN N/A
   URL http://www.astm.org/SSMS
   ImpactF N/A
   H-Index N/A
   SJR N/A
   Since 2017
   Volumes 0
   Issues 0
   Articles 0
   EiC Sudarsan Rachuri
   Board and Editors 1) Darek Ceglarek 2) Karl R. Haapala 3) Yinlun Huang 4) Jacqueline Isaacs 5) Sami Kara 6) Soundar Kumara 7) Sankaran Mahadevan 8) Lihong Qiao 9) Roberto Teti 10) Manoj Kumar Tiwari (See also Journal 11) Shozo Takata 12) Tetsuo Tomiyama 13) Li Zheng 14) Fazleena Badurdeen 15) Abdelaziz Bouras 16) Alexander Brodsky 17) LiYing Cui 18) Bryony DuPont 19) Sebti Foufou 20) Pasquale Franciosa 21) Robert Gao 22) Mon-eer Helu 23) Sanjay Jain 24) I. S. Jawahir 25) Sagar V. Kamarthi 26) Jay Kim 27) Minna Lanz 28) Kincho H. Law 29) Mahesh Mani 30) Raju Mattikalli 31) Michael W. Mckittrick 32) Shreyes N. Melkote 33) P. V. M. Rao 34) Utpal Roy 35) Christopher J. Saldana 36) K. Senthilkumaran 37) Gopalasamudram R. Sivaramakumar 38) Esvaran Subrahmanian 39) Dawn Tilbury 40) Con-rad S. Tucker 41) Anahita Williamson 42) Paul William Witherell 43) Lang Yuan 44) Rakesh Agrawal 45) Dean Bartles 46) Gahl Berkooz 47) Jian Cao 48) S. K. Gupta 49) Timothy G. Gutowski 50) Gregory A. Harris 51) Rob Ivester 52) Mark Johnson 53) Thomas Kurfess 54) Bahram Ravani 55) William C. Regli 56) S. Sadagopan 57) Vijay Srinivasan 58) Ram D. Sriram 59) Fred van Houten 60) Albert J. Wavering

19. Powder Metallurgy Progress
   Publisher DE GRUYTER OPEN
20. 3D-Printed Materials and Systems

Publisher Springer
ISSN 2363-8389
URL http://www.springer.com/materials/journal/40861

ImpactF N/A
H-Index N/A
SJR N/A
Since N/A
Volumes 0
Issues 0
Articles 0

EiC Roger J. Narayan (See also Journals [15, 11])

Board and Editors 1) Vipul Dave 2) Mohan Edirisinghe 3) Sungho Jin 4) Soshu Kirihara 5) Sanjay Mathur 6) Mrityunjay Singh 7) Pankaj Vadgama
Furthermore, the following journals are identified from the literature relevant to this review. Journals catering specifically or explicitly to AM, RM, RP and 3D printing are listed above.

The list contains only journals with more than 2 publications. The goal for composing this list is to enable other researchers to identify possible publication venues for their work. The list is sorted by the number of publications in our bibliography for each identified journal. The number of each entry indicates the number of publications for the journal.

11 The International Journal of Advanced Manufacturing Technology (See Journal 1)
11 Rapid Prototyping Journal (See Journal 4)
7 Computer-Aided Design [33] ISSN: 0010-4485
6 Robotics and Computer-Integrated Manufacturing (See Journal 3)
6 Journal of Manufacturing Science and Engineering (See Journal 2)
5 Journal of Materials Processing Technology [34] ISSN: 0924-0136
4 International Journal of Computer Integrated Manufacturing [35] ISSN: 1362-3052
4 CIRP Annals - Manufacturing Technology [36] ISSN: 0007-8506
3 Journal of Manufacturing Systems [37] ISSN: 0278-6125
3 Computers in Industry [38] ISSN: 0166-3615
2 Virtual and Physical Prototyping (See Journal 6)
2 Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture [39] ISSN: 2041-2975

[33] http://www.journals.elsevier.com/computer-aided-design
[34] http://www.journals.elsevier.com/journal-of-materials-processing-technology
[35] http://www.tandfonline.com/toc/tcim20/current
[36] http://www.journals.elsevier.com/cirp-annals-manufacturing-technology
[37] http://www.journals.elsevier.com/journal-of-manufacturing-systems
[38] http://www.journals.elsevier.com/computers-in-industry
[39] http://pib.sagepub.com
4. Reviews on the Subject

The topic of AM in general and its special applications, technologies and directions is extensively researched and results published in literature. The growth of the number of publications as found by Google Scholar and Proquest is illustrated in the following figures (See Fig. 10 and Fig. 11).

An analysis of literature within this domain from sources (See Sect. 1.1.2) for scientific literature shows an increase in the number of published works from 2002 to 2016 of 41.3 % on average (See Fig. 10), respectively 26.1 % for the search engine Proquest. This number is from the average of the average growth of results found for keywords related to specific AM topics and AM related literature in general from http://scholar.google.com.

In this section we will present the findings of the analysis of available data on the scientific publications.

Specific aspects of AM, 3D printing and associated areas are topic of a number of reviews listed below. The list of reviews is compiled by searching on the previously mentioned search engines (See sect. 1.1.2) using a keyword
Figure 10: Average number of publications and annual average growth for the combined results from scholar.google.com for 2002–2016

Figure 11: Average number of publications and annual average growth for the combined results from proquest.com for 2002–2016
The keywords are “3D Printing” +Review/Survey/“State of the Art”, “Additive Manufacturing” +Review/Survey “State of the Art”, “Rapid Manufacturing” +Review/Survey “State of the Art”.

The time range for the search for reviews is restricted from 2005 to 2016. Following this literature search a backward search on the results is performed. From the 70 reviews identified we calculate the average number of authors per review to be 3.3 with an average length of 15.2 pages. The list is sorted chronologically with the general theme or domain of the review provided.

1. Dimitar Dimitrov, Kristiaan Schreve and N. de Beer [61]; General Introduction, Applications, Research Issues
2. Vladimir Mironov, Nuno Reis and Brian Derby [172]; Bioprinting, Technology
3. Ben Utela et al. [252]; New Material Development (Mainly Powders)
4. Abbas Azari and Sakineh Nikzad [21]; Dentistry, Applications in Dentistry
5. Hongbo Lan [143]; Rapid Prototyping, Manufacturing Systems
6. Daniel Eyers and Krassimir Dotchev [72]; Rapid Manufacturing, Mass Customisation
7. Ferry P. W. Melchels, Jan Feijen and Dirk W. Grijpma [170]; Stereolithography, Biomedical Engineering
8. Fabian Rengier et al. [207]; Medicine, Data Acquisition (Reverse-Engineering) using Image Data
9. R. Sreenivasan, A. Goel and D. L. Bourell [227]; Energy Consumption, Sustainability
10. Rupinder Singh [224]; Rapid Prototyping, Casting
11. R. Ian Campbell, Deon J. de Beer and Eujin Pei [44]; Application and Development of AM in South Africa
12. Benjamin Vayre, Frédéric Vignat and François Villeneuve [256]; Metal Components, Technology
13. Dongdong Gu et al. [93]; Metal Components, Technology, Terminology
14. Ferry P. W. Melchels et al. [169]; Medicine, Tissue and Organ Engineering
15. Kaufui V. Wong and Aldo Hernandez [271]; General, Technology
16. Lawrence E. Murr et al. [182]; Metal Components, EBM, Laser Melting
17. Shawn Moylan et al. [179]; Quality, Test Artifacts
18. Timothy J. Horn and Ola L. A. Harrysson [109]; General, Applications, Technology
19. Xibing Gong, Ted Anderson and Kevin Chou [90]; EBM, Powder Based AM
20. Flavio S. Fogliatto, Giovani J.C. da Silveira and Denis Borenstein [77]; Mass-Customization
21. K. P. Karunakaran et al. [125]; Rapid Manufacturing, Metal Object Manufacturing
22. Carl Schubert, Mark C. van Langeveld and Larry A. Donoso [217]; General
23. Irene J. Petrick and Timothy W. Simpson [195]; Economics, Business
24. Iulia D. Ursan, Ligia Chiu and Andrea Pierce [251]; Pharmaceutical Drug Printing
25. Jasper Cerneeels et al. [47]; Thermoplastics
26. Mohammad Vaezi, Hermann Seitz and Shoufeng Yang [253]; Micro-Structure AM
27. Nannan Guo and Ming C. Leu [97]; General, Technology, Materials, Applications
28. Olga Ivanova, Christopher Williams and Thomas Campbell [118]; Nano-Structure AM
29. Robert Bogue [30]; General
30. Samuel H. Huang et al. [113]; Socio-Ecological and Economy
31. Zicheng Zhu et al. [305]; Hybrid Manufacturing
32. Dazhong Wu et al. [272]; Cloud Manufacturing
33. Bethany C. Gross et al. [92]; Biotech, Chemistry
34. Brett P. Conner et al. [57]; Classification, Object Complexity
35. Brian N. Turner, Robert Strong and Scott A. Gold [248]; Thermoplastics, Physical Properties
36. David W. Rosen [210]; Design for Additive Manufacturing
37. Dimitris Mourtzis, Michael Doukas and Dimitra Berndaki [178]; Simulation
38. Douglas S. Thomas and Stanley W. Gilbert [242]; Economy, Cost
39. Gustavo Tapia and Alaa Elwany [239]; Process Monitoring, Quality
40. Hae-Sung Yoon et al. [291]; Energy Consumption
41. Jan Deckers, Jef Vleugels and Jean-Pierre Kruth [59]; Ceramics AM
42. Rouhollah Dermanaki Farahani, Kambiz Chizari and Daniel Therriault [74]; Micro-Structure AM
43. Siavash H. Khajavi, Jouni Partanen and Jan Holmström [131]; Supply Chain, Application
44. William E. Frazier [79]; Metal Components
45. Wu He and Lida Xu [102]; Cloud Manufacturing
46. Syed Hasan Massod [163]; Fused Deposition Modeling (FDM)
47. Brian N. Turner and Scott A Gold [247]; Thermoplastic AM, Material Properties
48. Carlos Mota et al. [177]; Medicine, Tissue Engineering
49. C. Y. Yap et al. [290]; SLM
50. Donghong Ding et al. [62]; Metal Components, Wire Fed Processes
51. Adamson et al. [11]; Cloud Manufacturing, Terminology
52. Jie Sun et al. [231]; Food Printing, Technology
53. Jin Choi et al. [54]; 4D Printing
54. K. A. Lorenz et al. [158]; Hybrid Manufacturing
55. Merissa Piazza and Serena Alexander [197]; General, Terminology, Academic
56. Omar A. Mohamed, Syed H. Masood and Jahar L. Bhowmik [176]; Process Parameter Optimization (FDM)
57. Seyed Farid Seyed Shirazi et al. [220]; Tissue Engineering, Powder Based AM
58. Sheng Yang and Yaoyao Fiona Zhao [288]; Design for AM, Complexity
59. Sofiane Guessasma et al. [95]; Design for AM, Process Parameter Optimization
60. Wei Gao et al. [83]; General, Technology, Engineering
61. Yong Huang et al. [115]; General, Technology, Research Needs
62. Zhong Xun Khoo et al. [133]; Smart Materials, 4D Printing
63. Hammad H. Malik et al. [162]; Medicine, Surgery
64. Jie Sun et al. [232]; Food Printing
65. Behzad Esmaeilian, Sara Behdad and Ben Wang [71]; Manufacturing
66. H. Bikas, P. Stavropoulos and G. Chryssoulouris [28]; General, Technology
67. Julien Gardan [84]; Technology, Engineering, Manufacturing
68. Swee Leong Sing et al. [223]; Metal Components, Medicine, Implants, Materials
4.1. Stakeholder Distinction

Different 3D printing technologies, machines and manufacturers as well as services target different clients for which we propose the following classification. Generally the discerning factors are 1. cost per machine 2. quality of print (e.g., surface quality, physical properties of object) 3. reliability of machine and 4. materials available. From literature the three classes of audience are apparent:

- consumer/end user
- professional user
- industrial application

For the consumer a very important factor is the cost of the printer itself with 45% of consumers are not willing to pay more than $US 299 for a 3D printer [164].

In recent years the price of entry level consumer 3D printers, especially for build-kits, decreased to about $US 300 [47]. Open-source projects like RepRap have contributed to the decline of costs for these machines [225].

In Fig. 12 we differentiate between the user groups of end-users/consumer, professional users and industrial users. Industrial users rely on high quality available with a large selection of processable materials. Machines for these users are expensive and out of reach of most end-users and professional users. The quality these machines produce is very high and the objects can be used for integration in a product or be a product themselves. Due to these restrictions the availability of such machines is not very widespread but limited to highly specialised enterprises.

On the other end of the spectrum the end-user/consumer has a large choice of 3D printers to select from, they are relatively inexpensive, produce objects of acceptable quality, work on a much lower number materials (typically thermoplastics) and have a reliability that is lower than the reliability

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47 XYZPrinting da Vinci Jr. 1.0, $US 297.97, [https://www.amazon.com/XYZprinting-Vinci-Jr-1-0-Printer](https://www.amazon.com/XYZprinting-Vinci-Jr-1-0-Printer)

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of professional equipment. In the middle of the spectrum we see professional users, e.g., from design bureaus or architects, that use such machines in a professional manner, draw benefits from the usage of such technology but it is mostly not their main concept of business. In an example, an architect makes use of a 3D printer for the creation of a high-quality model of a building he designed, which is faster and easier than making such a model by hand.

![Audience classification and Expectations](image)

Figure 12: Audience classification and Expectations

5. 3D Printing Services

There are numerous dedicated 3D printing services available to end-users, professionals and industrial users. They differ in the clients they address, the services they offer, the quality they can provide and the cost they charge. In this section we give an overview of a selection of available 3D printing services. The list is not conclusive as a number of enterprises does offer 3D printing services in their portfolio but they are not necessarily to be considered 3D printing services due to either their local mode of operation or the number of 3D printers the user can chose from. This overview is closely based on the work of [204] and extends its findings.

We use the following list of properties to distinguish the services:

- The target group (End-users, industrial users or professional users)
- The local reach (Local or global)
• Availability of an API
• Services rendered (Design, 3D printing, marketplace, other)

Rayna and Striukova [201] base their exploratory study on the following list of services they have identified. For the original list of services we add the following information.

• 3D Burrito[^1] - Pre-Launch Phase
• 3D Creation Lab[^2]
• 3DLT[^3] - Shut down on 2015-12-31
• 3DPrintUK[^4]
• Additer.com[^5] - Unreachable
• Cubify Cloud[^6] - Acquired by 3D Systems, Service no longer available
• i.Materialise[^7]
• iMakr[^8]
• Kraftwürx.com[^9]
• MakerBot/Thingiverse[^10]
• MakeXYZ[^11]
• Ponoko[^12]

[^1]: http://3dburrito.com
[^2]: http://www.3dcreationlab.co.uk
[^3]: http://3dl.com
[^4]: https://www.3dprint-uk.co.uk
[^5]: http://additer.com
[^6]: http://cubify.com
[^7]: https://i.materialise.com/
[^8]: http://imakr.co.uk
[^9]: http://www.kraftwurx.com
[^10]: http://thingiverse.com
[^11]: https://www.makexyz.com
[^12]: https://www.ponoko.com/
For this study we extend the selection with the additional services listed in Tabs. 1 and 2. Services omitted in these two tables are described in the original study.

In contrast to the authors of the original work we think that an exhaustive list of such services is impossible to compile as a large number of local businesses do offer 3D printing services over the Internet and would therefore qualify to be included in such a list. These (local) businesses are hard to identify due to their limited size and reach. Also, an exhaustive list would need to contain 3D printing services and repositories of which many similar and derivative services exist.

Further, we extend the classification and study to the provisioning of an API by the respective service. An API should provide methods to use the service programmatically. With an API such printing services can be used as a flexible production means in CM settings. The range of functionality of such APIs can vary significantly and range from the possibility of having a widget displayed on a website with a 3D model viewer, to upload and store digital models in a repository, request quotes for manufacturing or digital fabrication. A commonality for these APIs is the requirement for the third-party user to have an account with the service, which is indicated in Tabs. 3 and 4 by Implementer in the column Required for registration. The indication User in this column indicates that the user must be registered with this service too.

The implementer registration is intended for scenarios where the API is embedded in a service or website that a third party user then uses. The findings of this study are presented in Tabs. 3 and 4 where we state whether the service provides an API and if it is publicly available or only accessible for business partners, who needs to be registered for the usage of the API and what capabilities the API provides (See Tab. 5).

This explorative extension study is performed as described by the original authors.

60 https://www.sculpteo.com
61 http://www.shapeways.com/
| Company/Service Name | URL                                      | Classification          | Established | Location |
|----------------------|------------------------------------------|-------------------------|-------------|----------|
| 3Faktur              | http://3faktur.com                       | Modeling Service       | 2014        | Germany  |
| 3DaGoGo              | https://www.3dagogo.com                  | Marketplace            | 2013        | USA      |
| 3DExport             | https://3dexport.com                     | Marketplace, Repository | 2004        | USA      |
| 3DHubs               | http://3dhubs.com                        | Crowd Printing Provider | 2013        | USA      |
| 3DPrinterOS          | https://www.3dprinteros.com              | Crowd Printing Provider | 2014        | USA      |
| 3DShook              | http://www.3dshook.com                   | Marketplace, Subscription Service | 2014 | Israel |
| 3D Warehouse         | https://3dwarehouse.sketchup.com         | Marketplace, Community, Repository | 2006 | USA |
| Autodesk 123D        | http://www.123dapp.com                   | Software, Marketplace, Repository | 2009 | USA |
| Clara.io             | https://clara.io                         | Repository, Modeling    | 2013        | Canada  |
| CreateThis           | http://www.createthis.com                | Marketplace            | 2013        | USA      |
| Cults                | https://cults3d.com                      | Marketplace, Repository, Design Service | 2013 | France |
| Grabcad              | https://grabcad.com                      | Software, Marketplace, Repository | 2009 | USA |
| La Poste             | http://impression3d.laposte.fr           | Print Provider, Marketplace | 2013 | France |
| Libre3D              | http://libre3d.com                       | Marketplace, Repository | 2014        | USA      |
| Makershop            | https://www.makershop.co                 | Marketplace, Repository | 2013        | USA      |
| Materflow            | http://www.materflow.com                 | Print                  | 2013        | Finland  |
| Company/Service Name         | URL                        | Classification                                                                 |
|-----------------------------|----------------------------|-------------------------------------------------------------------------------|
| NIH 3D Print Exchange       | http://3dprint.nih.gov     | Co-Creation, Repository                                                       |
| p3d.in                      | https://p3d.in             | Modeling                                                                      |
| Pinshape                    | https://pinshape.com       | Marketplace                                                                   |
| REPABLES                    | http://repables.com        | Repository                                                                     |
| Rinkak                      | https://www.rinkak.com     | Marketplace, Repository, Crowd Printing Provider                             |
| shapeking                   | http://www.shapeking.com   | Marketplace, Repository                                                      |
| Shapetizer                  | https://www.shapetizer.com | Marketplace, Repository, Print Provider                                       |
| Sketchfab                   | https://sketchfab.com      | Marketplace, Repository                                                      |
| stlfinder                   | http://www.stlfinder.com  | Search Engine, Repository                                                     |
| STLHive                     | http://www.stlhive.com     | Marketplace, Repository                                                      |
| Stratasys Direct Express    | https://express.stratasysdirect.com | Print Provider                                                               |
| Threeding                   | https://www.threeding.com  | Marketplace                                                                   |
| Tinkercad                   | https://www.tinkercad.com  | Print Provider, Design, Repository                                            |
| Treatstock                  | https://www.treatstock.com | Marketplace, Community, Crowd Printing Provider                             |
| trinckle                    | https://www.trinckle.com   | Print Provider                                                               |
| Trinpy                      | https://www.trinpy.com     | Marketplace, Subscription Service                                             |
| Company / Service Name | Provides an API | Required for registration | Capabilities Reach Target Group |
|------------------------|----------------|--------------------------|---------------------------------|
| 3Faktur                | No            | N/A                      | Regional, Consumer              |
| 3DaGoGo                | No            | N/A                      | Global, Consumer                |
| 3DExport               | No            | N/A                      | Global, Consumer + Professional |
| 3D Hubs                | Yes           | Implementer + User       | Global, Consumer                |
| 3D Printer OS          | No            | N/A                      | Global, Consumer                |
| 3D Print UK            | No            | N/A                      | Global, Consumer                |
| 3D Shook               | No            | N/A                      | Global, Consumer                |
| 3D Creation Lab        | No            | N/A                      | Global, Consumer                |
| 3D Warehouse           | No            | N/A                      | Global, Consumer                |
| Autodesk 123D          | N/A           | No                       | Global, Consumer + Professional |
| Clara.io               | Yes           | (not public)             | Implementer, Global, View, Retrieve, Global, Consumer + Professional |
| CreateThis             | No            | N/A                      | Global, Consumer                |
| Cults                  | Yes           | (not public)             | Implementer, Global, View, Retrieve, Global, Consumer + Professional |
| Grabcad                | No            | N/A                      | Global, Consumer + Professional |
| iMakr                  | No            | N/A                      | Global, Consumer                |
| i.Materialise          | Yes           | (not public)             | Implementer, Global, View, Retrieve, Quoting, Order, Global, Consumer + Professional |
| Kraftwürx.com          | Yes           | (not public)             | Implementer, Global, Order, Global, Consumer |
| La Poste               | No            | N/A                      | Regional, Consumer              |
| Libre3D                | No            | N/A                      | Global, Consumer                |
| MakerBot / Thingiverse| Yes           | Implementer              | Global, Consumer + Professional |
| Makershop              | Yes           | Search, Retrieve         | Global, Consumer + Professional |
| MakeXYZ                | Yes           | Implementer + User       | Global, Consumer + Professional |
| Materflow              | No            | N/A                      | Global, Consumer                |
| MeltWerk               | Yes           | (not public)             | Implementer, Global, View, Retrieve, Global, Consumer |
| Company / Service Name         | Provides an API | Required for registration | Capabilities                  | Target Group     |
|-------------------------------|-----------------|----------------------------|-------------------------------|------------------|
| NIH 3D Print Exchange         | Yes             | Implement, Upload, Retrieve | Global                        | Consumer         |
| p3d.in                        | No              | N/A                        | N/A                           | Global           | Consumer         |
| Pinshape                      | No              | N/A                        | N/A                           | Global           | Consumer         |
| Ponoko                        | No              | N/A                        | N/A                           | Global           | Consumer         |
| REPABLES                      | No              | N/A                        | N/A                           | Global           | Consumer         |
| Rinkak                        | Yes             | Implement, View, Order, Modeling | Global                        | Consumer         |
| Sculpeo                       | Yes             | Implement, Upload, + User Retrieve, Quoting, Order | Global                        | Consumer + Professional |
| shapeking                     | No              | N/A                        | N/A                           | Global           | Consumer         |
| Shapetizer                    | No              | N/A                        | N/A                           | Global           | Consumer         |
| Shapeways                     | Yes             | Implement, Upload, + User Quoting, Order | Global                        | Consumer + Professional |
| Sketchfab                     | Yes             | Implement, Upload, View     | Global                        | Consumer         |
| stlfinder                     | No              | N/A                        | N/A                           | Global           | Consumer         |
| STLHive                       | No              | N/A                        | N/A                           | Global           | Consumer + Professional |
| Stratsys Direct Express       | No              | N/A                        | N/A                           | Regional         | Professional     |
| Threeding                     | No              | N/A                        | N/A                           | Global           | Consumer         |
| Tinkercad                     | No              | N/A                        | N/A                           | Global           | Consumer         |
| Treatstock                    | Yes             | Implement, Upload, Retrieve | Global                        | Consumer         |
| trinckle                      | No              | N/A                        | N/A                           | Global           | Consumer + Professional |
| Trinpy                        | No              | N/A                        | N/A                           | Global           | Consumer         |
| TurboSquid                    | No              | N/A                        | N/A                           | Global           | Consumer + Professional |
| UPS                            | No              | N/A                        | N/A                           | Regional         | Consumer         |
| Yeggi                         | Yes             | Implement, Search, Retrieve | Global                        | Consumer         |
| Company / Service Name | Design marketplace | Design repository | Design service | Printing marketplace | Printing service | Printer sale | Crowd sourcing platform | Editor |
|------------------------|--------------------|-------------------|---------------|---------------------|-----------------|-------------|------------------------|--------|
| 3Faktur                |                    | +                 |               |                     |                 |             |                        |        |
| 3DaGoGo               | +                   | +                 |               |                     |                 |             |                        |        |
| 3DExport              | +                   | +                 |               |                     |                 |             |                        |        |
| 3DHubs                |                     | +                 |               |                     |                 |             |                        |        |
| 3DPrinterOS           |                     | +                 |               |                     |                 |             |                        |        |
| 3DPrintUK             | +                   | +                 |               |                     |                 |             |                        |        |
| 3DShook               | +                   | +                 |               |                     |                 |             |                        |        |
| 3D Creation Lab       |                     | +                 |               |                     |                 |             |                        |        |
| 3D Warehouse          | +                   | +                 |               |                     |                 |             |                        |        |
| Autodesk              | +                   | +                 |               |                     |                 |             |                        |        |
| 123D                  |                     | +                 |               |                     |                 |             |                        |        |
| Clara.io              | +                   | +                 |               |                     |                 |             |                        | +      |
| CreateThis            | +                   | +                 |               |                     |                 |             |                        |        |
| Cults                 | +                   | +                 | +             |                     |                 |             |                        | +      |
| Grabcad               | +                   | +                 |               |                     |                 |             |                        |        |
| iMakr                 |                     |                   |               |                     |                 |             |                        | +      |
| i.Materialise.com     | +                   | +                 | +             |                     |                 |             |                        | +      |
| Kraftwürx.com         |                     | +                 | +             |                     |                 |             |                        | +      |
| La Poste              | +                   | +                 |               |                     |                 |             |                        | +      |
| Libre3D               | +                   | +                 |               |                     |                 |             |                        |        |
| MakerBot / Thingiverse|                    |                    |               |                     |                 |             |                        | p +    |
| Makershop             | +                   | +                 |               |                     |                 |             |                        | +      |
| MakeXYZ               | +                   | +                 |               |                     |                 |             |                        | +      |
| Materflow             | +                   | +                 |               |                     |                 |             |                        | +      |
| MeltWerk              |                     |                   |               |                     |                 |             |                        | +      |
| MyMiniFactory         | +                   | +                 |               |                     |                 |             |                        | +      |
| NIH 3D Print Exchange | +                   | +                 |               |                     |                 |             |                        | +      |
| p3d.in                | +                   | +                 |               |                     |                 |             |                        | 48     |
| Pinshape              | +                   | +                 |               |                     |                 |             |                        | +      |
| Ponoko                | +                   | +                 |               |                     |                 |             |                        |        |
| REPABLES              | +                   | +                 |               |                     |                 |             |                        |        |
| Rinkak                | +                   | +                 |               |                     |                 |             |                        | +      |
| Sculpteo              | +                   | +                 |               |                     |                 |             |                        | +      |
| Shapeking             | +                   | +                 |               |                     |                 |             |                        | +      |
| Shapeways             |                     |                   |               |                     |                 |             |                        | +      |
| Sketchfab             | +                   | +                 |               |                     |                 |             |                        | +      |
| STLHive               | +                   | +                 |               |                     |                 |             |                        | +      |
| Stratasys Direct      |                     |                   |               |                     |                 |             |                        | +      |
| Threeding             | +                   | +                 |               |                     |                 |             |                        | +      |
| Tinkercad             | +                   | +                 |               |                     |                 |             |                        | +      |
| Treatstock            |                     |                   |               |                     |                 |             |                        | +      |
| Trinpy                |                     |                   |               |                     |                 |             |                        | +      |
| TurboSquid            | +                   | +                 |               |                     |                 |             |                        | +      |
| UPS                   | +                   | +                 |               |                     |                 |             |                        | +      |
| Watertight            | +                   | +                 |               |                     |                 |             |                        | +      |
| Yeggi                 | +                   | +                 |               |                     |                 |             |                        | +      |
| YouMagine             | +                   | +                 |               |                     |                 |             |                        | +      |
As analysed in Tab. 5, the services surveyed offer a different range of services each. No provider could be identified that offers a complete set of service for 3D printing and related tasks. In the table, the indication of \( p \) marks companies that do not themselves offer printers through this service but their parental companies do. The \( o \) character in the column for printing service for Tinkercad and YouMagine, indicates that the service itself does not render printing services, but has a cooperation with a third party for the provisioning of this service. With the exception of La Poste, UPS and iMakr all the services render their business completely on the Internet without the requirement for physical interaction. La Poste and UPS offer an Internet interface with the physical delivery of the objects in certain shops of theirs. Services that offer a design market place can offer designs and other files costless or for a fee, no distinction is made for this study. Yeggi and stlfinder are search engines for 3D model data that work on the data from other sources. Albeit a search engine, Yeggi provides the integration of printing services and cloud printing services for models available from third party services, thus Yeggi can be classified as a service of services. The service rendered by Trinpy is subscription based with various membership options. Grabcab provides 3D printing planning and control services, and integration with an online editor.

6. Review

Cloud Manufacturing is mainly an overlapping manufacturing or engineering concept with application and grounding the development of parts or objects in “traditional” manufacturing. With traditional manufacturing we denote all technologies and methods to create or fabricate objects or parts other than AM. For a distinction between manufacturing methods see Klocke [136], Nee [185] and the DIN Standard 8580 [1]. In this sense all subtractive or formative manufacturing methods are summarises as “traditional manufacturing” methods. As AM offers a large degree of flexibility due to short lead times as well as other beneficial properties, we see that AM is the ideal technology to be considered within CM scenarios. Taking the properties of AM into account we do not predict that AM will replace other manufacturing methods, not even within CM scenarios. Rather AM will fill niches for special applications like mass-customisation, rapid replacement production capabilities or RT, especially within CM scenarios. With this work we aim to contribute to the development of AM methodology and
technology in the CM paradigm.

6.1. Topological Map

In Fig. 13 the relationship and connection of various concepts relevant to CM is described. This map forms the basis of the following review, where the nodes from the map represent sections from the review where we present the current state of research and elaborate on open research questions. The topics are extracted from literature.

This topological map displays the relationship of CM with a variety of connected and enabling technologies and concepts. Additive Manufacturing (See Sect. 6.10) enables CM to be more modular, flexible and offers new capabilities and business opportunities. The Rapid Technology (See Sect. 6.8) and its composition Rapid Prototyping (RP, see Sect. 6.8.3), Rapid Manufacturing (RM, see Sect. 6.8.2) and Rapid Tooling (RT, see Sect. 6.8.1) are areas in which CM can be applied. The topic of Service Orientation (Sect. 6.7) and its composition “as-a-Service” of which Design-as-a-Service (DaaS, see Sect. 6.7.2), Testing-as-a-Service (TaaS, see Sect. 6.7.3) and Manufacturing-as-a-Service (MaaS, see Sect. 6.7.1) are explored as examples, are concepts that enable the efficient application of CM. For a broader understanding it is required to research the stakeholders involved in this technology which makes Sect. 6.6. The topics of Scheduling (See Sect. 6.12) and Resource Description (See Sect. 6.13) are to be discussed for the universal and efficient application of CM. The domain of Simulation (See Sect. 6.5) with its composition of Optimisation (See Sect. 6.5.2) and Topological Optimisation (See Sect. 6.5.1) enable a more rapid, more flexible and more robust usage of the technology. For AM technology the application of Topology Optimisation enables the benefits of this technology. Similar to AM is 3D printing (See Sect. 6.4) with its subtopic of Accuracy and Precision (See Sect. 6.4.1) as this technology is a appropriate basis for CM systems. The topic of Hybrid Manufacturing (See Sect. 6.14) gains importance in flexible and agile manufacturing systems which warrants and requires its research. In the topic of Technology (See Sect. 6.2) the general principles and technologies of CM and AM are discussed as these are basic principles for the efficient implementation of these systems. The topic of Cloud Computing (CC, see Sect. 6.11) with its sub-components Internet of Things (IoT, see Sect. 6.11.1) and Cyber-physical Systems (CPS, see Sect. 6.11.2) is the conceptual progenitor of CM and therefore requires careful studying. IoT and CPS are key enabling technologies for CM. The topic of Security 6.3 is of increasing importance with the
spreading application of AM and CM as attack surfaces grow and potential damage increases.

6.2. Technology

A large number of technologies and technological advances have made AM possible to evolve from its origin as a RP method to its current state where it is used for end-part manufacturing (RM) and available to consumers [88, 269]. All 3D printed objects are based on a digital model. This model can either be created using CAD software, 3D sculpting software or acquired using reverse-engineering methods (e.g., object scanning or photo reconstruction) [89].

Albeit direct slicing from a CAD model has been proposed by Jamieson [119] in 1995 it is still rarely performed. Direct slicing requires implementation in the CAD software for each printer type and printer manufacturer, which is not feasible. Further shortcomings of the de-facto standard file format for AM, i.e., STL, namely the possibility to contain mis-aligned facets, holes or to be non-watertight, as well as being to large in file size are reported by [281].
Besides a Steiner-patch based file format to replace the STL file format the ASTM Committee F42 has published an ISO Standard for the AMF (Additive Manufacturing File Format) with the same intention. Both file formats are created to increase the accuracy for the models described and therefore increase the quality of the resulting printed objects. STL seems to be the prevalent file format for AM with 25700 results on Google Scholar compared to 8230 results for AMF. Further investigation in the file support for different hard- and software vendors is warranted but out of the scope of this work.

The review by Dimitrov et al. presents further information on the technology that AM is based on with an overview of applications for it.

In the review by Esmaeilian et al. the authors present the relationship of AM and Manufacturing in general as well its benefits. With the emergence of Internet or cloud based CAD Modelling software the creation of models for AM becomes easier as direct integration of 3D printing providers is possible.

Furthermore, the collaborative aspect of 3D modelling is enhanced as studied by Jou and Wang. This study used a group of college students as a test group and investigated the adoption of an online CAD modelling (Autodesk AutoCAD) software in the curriculum.

The authors Andreadis et al. present a case study on the adoption of an unnamed cloud based CAD system in comparison to traditional software, as well as an exhaustive list of benefits of cloud based software.

Wu et al. present an economic analysis of cloud based services for design and manufacturing. This work also explores a number of cloud based services along with their pricing.

Communities are of great importance to enterprises as shown in West and Kuk. One form of community is a repository for 3D printable digital models that collects and curates models supplied by users for collaboration, exchange, co-creation and sale. In this work the authors conduct a study to research the profit of catering for such a community/repository (Thingiverse) by a former open-source company (Makerbot).

Wittbrodt et al. performed experiments to determine the ROI (Return on Investment) of 3D printers for common households and their feasibility in application in end-user scenarios. With their experiment they concluded that an average household can achieve between 40 and 200 percent

\[\text{http://autodesk.com/products/autocad}\]
ROI on average usage of such machines.

6.3. Security

Security for 3D Printing, AM or CM can be discussed from at least three perspectives. The first perspective would be the legal security of data and models processed within such a scenario. Discussions can range from whether it is legal to manufacture an existing object (replication) which might be protected by intellectual copyright laws to questions regarding product liability in case of company supplied model data. The second perspective is closely related to intellectual property (IP) as it is the technological discussion about the safeguarding of digital model files and data. The third perspective is about the data and process security itself in scenarios with malicious third-parties (e.g., Hackers, Cyber-criminals). This third perspective is not limited to AM but shares many problems with CC and computing in general.

Dolinsky [65] analyses the copyright and its application to 3D Printing for the jurisdiction of the USA. Because legal systems are different to each other such an analysis can not be exhaustive.

Grimmelmann [91] further exemplifies the legal status of 3D printing and model creation in the USA with fictitious characters from literature and theatre. He states that the creation of an object irregardless of the source of model for such a creation is infringing on copyright if the object that is replicated is protected by copyright.

In [260] the author discusses the current situation of 3D printing in regard to gun laws. This discussion was started by the media in 2013 as models for a functional plastic gun were distributed and the gun manufactured. The author states that current gun control laws are adequate to control 3D printed weapons and that this is currently not a big issue.

On a broader scope the authors McNulty et al. [167] research the implications of AM for the national security of the USA where the authors present the benefits of bio or tissue 3D printing for the treatment of battlefield wounds as well as the implications of AM technologies for criminal misconduct.

For the analysis of data security the authors Wu et al. [276] present the importance of such technologies within a CM environment. They propose the development of trust models for cyber-physical systems respectively the actors within such systems.

The authors of Yampolskiy et al. [284] provide a full risk analysis of a scenario for outsourcing AM under consideration of IP. The risk assessment
does not include malicious behaviour other than IP infringement.

To secure printed objects against counterfeiting the authors of [75] study and recommend the use of chemical components for authentication. Possible attacks on the 3D printing process by third parties is researched in [294] where one scenario is about the introduction of wilfully integrated material differences into an object in order to weaken the object under load. If the printing process itself is secured the question remains if a printed object is the original, a genuine replicate or a faked replicate. For the identification of genuine objects the authors of [14] research the applicability of physical signatures to 3D printed objects.

In [110] the authors present a watermarking technique for 3D printed objects that is resilient against repeated digital scanning of the manufactured object.

For a generalised discussion on security of cloud services and cloud computing we refer to [230] where the authors present issues ranging from data integrity to confidentiality. The concepts and terminology of CC security are also discussed in [306] of which the concept of confidentiality, trust and privacy are most relevant to scenarios of cloud based AM where users have physical objects created from digital models by third parties.

Sturm et al. [229] present attack scenarios and mitigation strategies for attacks on AM system. The authors see rising CPS implementations in AM as potential intrusion vectors for attacks. The authors discuss various attacks for each of the manufacturing process phases. Furthermore, the authors identify the STL file format as a potential risk for tampering and attacking. Among the recommendations for mitigation is file hashing and improved process monitoring.

Bridges et al. [39] briefly explore possible attacks on the cyber-physical systems that are used for AM. Among the attack scenarios the authors identify theft and tampering.

6.4. 3D Printing

Following the distinction between AM and 3D printing given in the definition of 3D printing (See Sect. 2.1.2) by some authors into high-quality professional or industrial usage and lower-quality end-user or semi-professional usage 3D printing could not be part of CM. As we relax the definition of AM and 3D printing and use the terms as synonyms, we survey technological developments within this chapter. Technological progress and development
are essential to the widespread use and application of 3D Printing or AM in the CM paradigm.

In the short article by Hansen et al. [100] the authors propose a measurement method for the correction or calibration of FDM printers. For this purpose the authors develop a measurement plate that is printed with specified parameters. In their experiment the authors recorded roundness errors of up to 100 µm. The calibration could not be applied due to the printer control software being closed-source.

Anitha et al. [19] analyse the process variables layer thickness, bead width and deposition speed for their influence on the quality of objects manufactured using FDM. The authors find that the layer thickness is contributing with approximately 50% to the surface roughness of the manufactured objects.

Balogun et al. [22] describe an experiment on the energy consumption and carbon footprint of models printed using FDM technology. They define three specimens of 9000 mm³ and 18000 mm³ volume which are printed on a Stratasys dimension SST FDM. Their experiment also captures the energy consumption of the post processing with an ultrawave precision cleaning machine. The energy consumed for the print is approximately 1 kWh. Over 60% of the energy is consumed in non-productive states, e.g., pre-heating. This energy consumption profile warrants high utilisation of 3D printers when aiming for a low ecological impact and penalises frequent and long idle times of the 3D printer.

Brajlih et al. [37] propose a comparison method for the speed and accuracy of 3D printers. As a basis the authors introduce properties and capabilities of 3D printers. A test-object designed by the authors is used to evaluate the average manufacturing speed of an Objet EDEN330 Polyjet and 3D Systems SLA3500 SLA manufacturing machine in an experiment. Furthermore, the experiment includes an EOS EOSINT P385 SLS and Stratasys Prodigy Plus FDM machine. The experiment concludes that the SLS machine is capable of the highest manufacturing speed (approx. 140 cm³/h). In the experiment the angular and dimensional deviations are significant (up to 2.5° for a 90° nominal, and 0.8 mm for a 10 mm nominal).

Roberson et al. [208] develop a ranking model for the selection of 3D printers based on the accuracy, surface roughness and printing time. This decision making model is intended to enable consumers and buyers of such hardware to select the most appropriate device.

Utela et al. [252] provide a review on the literature related to the devel-
opment of new materials for powder bed based 3D printing systems. They decompose the development into five steps, for which they provide information on the relevant literature.

Brooks et al. [40] perform a review on the history and business implications of 3D printing. They argue that the most promising approach for companies to benefit from 3D printing technology is to invest in and adapt current business models to support supplementary printing for the users. They also present the importance of the DMCA (Digital Millennium Copyright Act) in the USA under the aspect of 3D printing for current and upcoming businesses and services in the USA.

Bogue [30] aims to provide an introduction into 3D printing with this review. The historical development of the various printing technologies is presented and furthermore, applications with examples are explored.

Petrick and Simpson [195] compare traditional manufacturing, which they classify as “economy of scale”, with AM. AM is classified by the authors as “economy of one”. They base their future hypotheses on the traditional design-build-deliver model and current patterns in supply chains from which they draw logical conclusion for future developments. These hypotheses are sparsely supported by literature. They predict that in the future the boundaries between the design-build-deliver paradigm will be less clear and that design and production will be closely coupled with experiments. One obvious prediction is that the supply chains will get shorter and the production will be more localised both geographically and in regard to time planning.

Matias and Rao [164] conduct an exploratory study on the business and consumer markets of 3D printing. This study consists of a survey based part for consumers within the area of 3D printing with a sample size of 66 participants conducted in 2014. One of their findings for the consumers is the willingness of 45% of the participants to spend only $US 299 on this technology. They also found out that a large number of consumers is not proficient with the technology and the required software. This finding was backed by five interviews conducted with business persons from five different companies. Their interviewees also expressed concerns that there will not be mass market for 3D printing within the next five to ten years.

6.4.1. Accuracy/Precision

The accuracy, precision and geometrical fidelity of 3D printed objects has been researched in many works for over 20 years [116, 73] due to the necessity to produce objects that match their digital models closely. This topic is of
general relevance for AM as only precise objects are usable for the various applications. Increased precision and accuracy enables AM and CM to be a valid manufacturing technology.

Dimitrov et al. [61] conducted a study on the accuracy of the 3DP (3D-Printing) process with a benchmark model. Among the three influencing factors for the accuracy is the selected axis and the material involved.

Turner and Gold [247] provide a review on FDM with a discussion on the available process parameters and the resulting accuracy and resolution.

Boschetto and Bottini [32] develop a geometrical model for the prediction of the accuracy in the FDM process. They predict the accuracy based on process parameters for a case study for 92 % of their specimens within 0.1 mm.

Armillotta [20] discusses the surface quality of FDM printed objects. The author utilises a non-contacting scanner with a resolution of 0.03 mm for the assessment of the surface quality. Furthermore, the work delivers a set of guidelines for the FDM process in respect to the achievable surface quality.

Equbal et al. [69] present a Fuzzy classifier and neural-net implementations for the prediction of the accuracy within the FDM process under varying process parameters. They achieve a mean absolute relative error of 5.5 % for the predictor based on Fuzzy logic.

Sahu et al. [213] also predict the precision of FDM manufactured parts using a Fuzzy prediction, but with different input parameters (Signal to noise ratio of the width, length and height).

Katatny et al. [126] present a study on the dimensional accuracy of FDM manufactured objects for the use as medical models. The authors captured the geometrical data with a 3D Laser scanner at a resolution of 0.2 mm in the vertical direction. In this work a standard deviation of 0.177 mm is calculated for a model of a mandible acquired from Computer Tomography (CT) data.

To counter expected deviations of the object to the model, Tong et al. [243] propose the adaption of slice files. For this adaption the authors present a mathematical error model for the FDM process and compare the adaption of slice files to the adaption of STL (STereoLitography) files. Due to machine restrictions the corrections in either the slice file and the STL file are comparable, i.e., control accuracy of the AM fabricator is not sufficient to distinguish between the two correction methods.

Boschetto and Bottini [33] discuss the implications of AM methods on the process of design. For this discussion they utilise digitally acquired images
to compare to model files.

Garg et al. [87] present a study on the comparison of surface roughness of chemically treated and untreated specimens manufactured using FDM. They conclude that for minimal dimensional deviation from the model the objects should be manufactured either parallel or perpendicular to the main axis of the part and the AM fabricator axis.

6.5. Simulation

Simulation in the area of AM is of great importance even though the process of object manufacturing itself is relatively cheap and fast when compared to other means of production. But even 3D printed objects can take many hours to be manufactured in which the AM resource is occupied. Furthermore, with specialised and high value printing materials the costs can be prohibitively expensive for misprinted parts.

In [104] the authors describe a voxel based simulation for 3D printing for the estimation of the precision of AM objects.

Pal et al. [189] propose a finite-element based simulation for the heat-transfer of powder based AM methods. With this simulation the authors claim that the general quality of the printed objects can be enhanced and post-processing/quality-control can be reduced.

The work of Zhou et al. [301] proposed a numerical simulation method for the packing of powder in AM. This research is conducted to provide a better understanding of the powder behaviour in methods like SLS or SLM.

Alimardani [15] propose another numerical simulation method for the prediction of heat distribution and stress in printed objects for Laser Solid Freeform Fabrication (LSFF), a powder based process similar to LENS. They compare their numerically computed predictions with experimental specimens, in one finding the maximum time-dependent stress could be reduced by eight percent by improvements made by the simulation.

Ding et al. [64] discuss a FEM based simulation model for wire and arc based AM. Their simulation of the thermo-mechanical properties during this process is performed in the ABAQUS software.

Chan [49] presents graphical simulation models for the use in manufacturing scenarios not limited to AM. Such models must be adopted to contain virtual production entities like the ones provided by CM.

http://www.3ds.com/products-services/simulia/products/abaqus
Mourtzis et al. [178] present a review on the aspects of simulation within the domain of product development (PD). For this work they give introduction to concepts and technologies supporting and enabling PD. The concepts are explained in sections of two paragraphs each and supported by existing literature. They link the concepts to simulation research within these areas, where applicable. The concepts and technology introduced includes Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Computer Aided Process Planning (CAPP), Augmented and Virtual Reality (AR and VR), Life Cycle Assessment (LCA), Product Data Management (PDM) and Knowledge Management (KM), Enterprise Resource Planning (ERP), Layout Planning, Process-, Supply Chain- and Material Flow Simulation, Supervisory Control and Data Acquisition (SCADA) and Manufacturing Systems and Networks Planning and Control. Their review is based on over 100 years of research in the area of simulation and 15954 scientific articles from 1960 to 2014. The articles are aligned with the product and production lifecycle. Furthermore, this review includes a comparison of commercially available simulation software. The authors conclude their work with a detailed analysis of research opportunities aligned to the concepts introduced within this work.

6.5.1. Topological Optimisation

One of the key benefits of AM is the ability to create almost any arbitrarily complex object which makes topological optimisation ideal for AM. In CM scenarios such optimisations can be embedded in the digital process chain and be offered and applied as services. In this section we present a number of research works on topological optimisation for AM.

In [48] the authors discuss the application of topology optimisation for AM in a general manner giving an overview of the current state.

Galantucci et al. [80] present experimental results of topology optimised and FDM printed objects from compression tests. In their experiment the reduction of filling material reduced the material consumption but also the maximum stress of the object.

Almeida and Bártilo [58] propose a topology optimisation algorithm for the use in scaffold construction for bio-printing. This optimisation strategy is aimed to create scaffolds that are more bio-compatible due to their porosity but yield high structural strength. The authors conducted an experiment for the comparison of the topological optimised structures and un-optimised structures with reduced infill. Their approach yields structurally stable scaf-
folds up to 60 % porosity.

The work by Leary et al. [146] focuses on the topological optimisation to create objects without the requirement for additional support structures. For this approach the authors perform a general topological optimisation first, then orient the part optimally to reduce the required support material and apply a strategy to add part structures to remove the required support material. In an experiment conducted the authors create an object that requires significantly less material (89.7 cm$^3$ compared to 54.9 cm$^3$) and is manufactured in 2.6 hours compared to 5.7 hours for the optimised part with support structures.

Tang et al. [233] propose a design method for AM with the integration of topological optimisation. For this work the authors analyse existing design methods for AM.

Bracket et al. [36] provide an overview and introduction of topology optimisation for AM. The authors identify constraints and restrictions for the usage of topology optimisation, e.g., insufficient mesh-resolution or insufficient manufacturing capabilities. Among the identified opportunities of topology optimisation in AM is the ability create lattice structures and design for multi-material objects.

Gardan [85] proposes a topology optimisation method for the use in RP and AM. The work is focused on the inner-part of the object. In non-optimised objects this is filled with a pre-defined infill pattern of a user-selectable density. The authors implement the method in a plugin for Rhinoceros 3D [64] and provide an experiment with SLA and SLS. The article does not provide detailed information on the implementation of the software and the algorithm.

Gardan and Schneider [86] expand on the prior work by Gardan by slightly expanding the previous article. In this work the authors apply the optimisation method to prosthetic hip implants and additionally experiment on a FDM 3D printer.

Hiller and Lipson [105] propose a genetic algorithm (GA) for the multi-material topological optimisation. With this approach the authors demonstrate the optimisation of varying degrees of stiffness within a part. They utilise a high-level description of the parts properties to design the desired object automatically in its optimised composition.

64 [https://rhino3d.com]
6.5.2. Optimisation

For AM and CM as processes a number of optimisations is possible and necessary. The optimisations can relate to the optimisation of process parameters for quicker manufacturing, higher quality manufacturing or increased utilisation of hard- and software resources. The optimisation can furthermore, regard the embeddability and integration of AM and CM within existing production processes.

Optimisation for AM is a topic that is researched for a long time, as illustrated by the following two articles. Cheng et al. [52] propose an optimisation method for the criteria of manufacturing time, accuracy and stability. This optimisation is based on the calculation of the optimal part orientation. As a basis for the optimisation, the authors analyse the sources for errors in AM processes, e.g., tessellation errors, distortion and shrinkage, overcuring or stair-stepping effects. For their model they weight input parameters according to the inflicting errors and perform a multi-objective optimisation.

Lin et al. [153] propose a mathematical model to reduce the process error in AM. In the first part the authors analyse the different process errors for various types of AM, e.g., under- and overfill, stair-stepping effects. Their model optimises the part orientation for minimal errors. Albeit this work is more than 15 years old, optimal orientation and placement of objects is not widely available in 3D printing control software.

More recently, Rayegani and Onwubolu [203] present two methods for the process parameter prediction and optimisation for the FDM process. The authors provide an experiment to evaluate the tensile strength of specimens for the optimised process parameters. For the optimised parameters the authors provide the solution of 0° part orientation, 50° raster angle, 0.2034 mm raster width and -0.0025 mm air-gap. These parameters yield a mean tensile strength of 36.8603808 MPa.

Paul and Anand [192] develop a system for the calculation of the energy consumption in SLS processes and process parameter optimisation to minimise the laser energy. For the model the authors neglect the energy consumption of all elements (e.g., heating bed) but the laser system.

Paul and Anand [194] propose an optimisation for AM for the reduction of support material. Their approach is to optimise the part orientation for the minimum of support material. Furthermore, they provide optimisation for minimum cylindricity and flatness errors.

Jin et al. [17] propose a method to optimise the path generation of ex-
trusion based AM, e.g., FDM. The optimisation goals for this approach are machine utilisation and object precision. The authors perform a study with their approach but comparison data on the quality and time consumption of other algorithms is missing.

Khajavi et al. [131] present an optimisation for the spare-parts industry of fighter jets by the utilisation of AM. This work is on a systemic optimisation with AM being one strategy to achieve the optimum solution. The authors analyse the current situation in this specific application and propose an optimised solution based on distributed manufacturing or AM.

Ponche et al. [199] present an optimisation for the design for AM based on a decomposition of functional shapes and volumes. The authors argue that objects designed for traditional manufacturing are not necessarily suitable for AM but require partial or complete re-design to adjust for the specifics of a certain AM process, e.g., in the inability to produce sharp corners and edges. In their work one optimisation goal is the reduction of material and therefore cost.

Hsu and Lai [111] present the results of an experiment and the resulting process parameter optimisation for the 3DP manufacturing method. The authors improved the dimensional accuracy of each axis to under 0.1 mm. Furthermore, the authors improved on the building time by approximately 10 % and on the flexural stress by approximately 30 %. The authors experimented on the four process parameters that are layer height, object location, binder saturation and shrinkage.

6.6. Stakeholder

In CM systems or cloud based printing systems naturally a number of stakeholders is involved. With this section we are presenting the current state in research on the identification of stakeholders in this domain as well as research regarding their agendas.

In Rayna and Striukova [204] the authors identify the requirements of end-users for online 3D printing services. They base their study on concepts relevant to these stakeholders like user-participation and co-creation.

Park et al. [190] provide a statistical analysis of patents and patent filings in the domain of 3D printing and bioprinting that can serve as a basis for decision making in the investment and R&D in these fields. The stakeholders in this case are the investors and managers.

Hämäläinen and Ojala [99] applied the Stakeholder Theory by Freeman on the domain of AM and performed a study on eight companies with semi-
structured interviews. They identified five companies that use AM for prototyping (RP). They further analysed the benefits of AM for the interviewed companies.

Buehler et al. [42] created a software called GripFab for the use in special needs education. For this software and the use of 3D printing in special needs education they performed a stakeholder analysis. The analysis is based on observations and found beneficial uses for this technology, e.g., in the form of assistive devices.

Munguía et al. [181] analyse what influence missing standards have on the stakeholders of RM and develop a set of best practises for RM scenarios. They identified the four main contributors to RM cost as Operation times, Machine costs, Labour costs and Material costs.

Lehmhus et al. [149] analyse the usage of data acquisition technologies and sensors within AM from the perspectives of the identified stakeholders designer, producer, user and regulatory or public bodies. They argue that the producers in such scenarios might become obsolete if AM is utilised in a complete CM sense.

Fox [78] introduces the concept of virtual-social-physical (VSP) convergence for the application to product development. Within this concept he argues that AM can play an integral part to enhance product development. He identifies requirements from stakeholders in the product development process and addresses them in this work.

Flatscher and Riel [76] propose a method to integrate stakeholder in an integrated design-process for the scenarios of next-generation manufacturing (Industry 4.0). In their study, a key challenge was the integration of all stakeholders in a team structure which they solved by integrating influential persons from different department in the joint operation.

Maynard [166] discusses the risks and challenges, that come with the paradigm of Industry 4.0. Industry 4.0 as a concept is incorporating other concepts like AM and CM. The author briefly identifies the possible stakeholders of this technology as consumers, CEOs and educators.

In the report by Thomas [241] the author performs a very detailed and thorough analysis of stakeholders for AM technology in the USA. The list of identified stakeholders is 40 entries long and contains very specific entries (e.g., Air Transport Providers or Natural Gas Suppliers) as well as generalised stakeholder groups (e.g., Professional Societies or Consumers).
6.7. Service Orientation

Service orientation denotes a paradigm from the domain of programming (Service Oriented Architecture, SOA). Within this paradigm the functionality or capability of a software is regarded and handled as a consumable service. The services offer encapsulated capabilities that can be consumed by users or other services in an easy to use, well-defined and transparent manner. The services are inter- and exchangeable within business processes as their inner-working is abstracted and the services act like black boxes with well-defined interfaces. With CM or AM in general, this service orientation can be expanded to the physical resources of manufacturing. Similar to service orientation from the programming domain, it must be bound by the same stringency of well-defined interfaces and transparent or abstract execution of functionality or capability.

In the review on service-oriented system engineering (SOSE) by Gu and Lago [94], the authors propose the hypotheses that the challenges in this domain can be classified by topic and by type. SOSE is the engineering discipline to develop service oriented systems. The authors identified 413 SOSE challenges from the reviewed set of 51 sources. The authors furthermore identified quality, service and data to be the three top challenges in this domain.

Wang et al. [263] provide a review on the CC paradigm. For this work the authors classify CC into the three layers (Hardware-as-a-Service - HaaS, Software-as-a-Service - SaaS and Data-as-a-Service - Daas). In this early work on CC the authors establish the importance of SoA for the CC paradigm.

Tsai et al. [246] present an initial survey on CC architectures and propose a service architecture for CC (Service-Oriented Cloud Computing Architecture - SOCCA) for the interoperability between various cloud systems. Among the identified problems with CC architectures are tight coupling, lack of SLA (Service Level Agreement) support, lack of multi-tenancy support and lack of flexibility in user interfaces. The authors utilise SOA for the implementation of their prototype that is deployed on Google App Engine[65].

Alam et al. [13] present a review on impact analysis in the domains of Business Process Management (BPM) and SOA. In their work the authors discuss the relationship and convergence of the two methods. From a set of 60 reviewed studies the authors conclude that BPM and SOA are becoming

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[65] https://appengine.google.com
dominant technologies.

Zhang et al. [296] propose a management architecture for resource service composition (RSC) in the domain of CM. For this work the authors analyse and define the flexibility of resources and their composition. The implementation by the authors supports resource selection based on QoS and flexibility.

Shang et al. [219] propose a social manufacturing system for the use in the apparel industry. Their implementation connects existing logistics and manufacturing systems with a strong focus on the consumer. For this architecture the authors rely heavily on SOA technology and describe the implementation of various layers required.

Tao et al. [235] analyse the development of Advanced Manufacturing Systems (AMS) and its trend towards socialisation. In this work the authors establish the relationship between service orientation and manufacturing. The authors identify three phases for the implementation of service-oriented manufacturing (SOM), namely “Perception and Internet connection of Manufacturing resource and capability and gathering, Aggregation, management, and optimal allocation of Manufacturing resource and capability in the form of Manufacturing service and Use of Manufacturing service”.

Thiesse et al. [240] analyse economic implications of AM on MIS (Management Information Systems) and the service orientation of these systems. In this work the authors analyse the economic, ecological and technological potential of AM and its services. The authors conclude that the services for the product development will be relocated upstream.

For the service composition of cloud applications standards and definitions are essential. In the work by Binz et al. [29] the authors introduce the TOSCA (Topology and Orchestration Specification for Cloud Applications) standard. Albeit this standard is focused on the deployment and management of computing and other non-physical resources its architectural decisions and structures are of relevance to CM systems. Support for encapsulation and modelling as described in this work is sparse for other CM systems.

As an extension to the previous work, the authors Soldani et al. [226] propose and implement a marketplace (TOSCAMART) for TOSCA for the distribution of cloud applications. Such a marketplace would be highly beneficial to CM systems as it can foster innovation, collaboration, re-use and competition.
6.7.1. Manufacturing-as-a-Service

Described in Sect. 6.7 the service orientation regards capabilities as services that can be consumed. Such a class of services is the manufacturing of products. As a consumer of such a service, one is not necessarily interested in the process of manufacturing (e.g., what type of machine is used) or the location of manufacturing as long as a pre-agreed upon list of qualities of the end-product is complied with. As an example it can be said that a user wants two parts made from a certain metal, within a certain tolerance, certain properties regarding stress-resistance and within a defined time frame. The input of this service would then be the CAD model and the properties that must be fulfilled. The parts could then either be milled or 3D printed in any part of the world and then shipped to the user. The user must pay for the service rendered, i.e., the manufacturing of objects, but is not involved with the manufacturing itself as this is performed by a service provider. In the seventh EU Framework Programme, the project ManuCloud\(^{66}\) was funded that consolidated research on this topic. In this section we present current research articles on the subject in order to illustrate the concept of MaaS, its role for CM and applications.

Tao et al.\(^{236}\) propose an algorithm for a more efficient service composition optimal-selection (SCOS) in cloud manufacturing systems. Their proposed method is named FC-PACO-RM (full connection based parallel adaptive chaos optimisation with reflex migration) and it optimises the selection of manufacturing resources for the quality properties time, cost, energy, reliability, maintainability, trust and function similarity. In an experiment they proof that their implementation performs faster than a genetic algorithm (GA), an adaptive chaos optimisation (ACO) algorithm for the objectives of time, energy and cost, but not for the objective of reliability.

Veiga et al. \(^{258}\) propose a design and implementation for the flexible reconfiguration of industrial robot cells with SMEs in mind. These robot cells are mostly reconfigurable by design but with high barriers for SMEs due to the requirement of experts. The system proposed enables an intuitive interface for reconfiguration of the cells in order to enhance the flexibility of manufacturing. The implementation draws heavily on SOA concepts. The implementation supports the flexible orchestration of robotic cells as services.

Zhang et al. \(^{297}\) provide an introduction into the paradigm of CM.

\(^{66}\) \url{http://www.manucloud-project.eu}
Within this work the authors discuss issues arising from the implementation and the architecture itself. The authors present the decomposition of this paradigm into its service components, that are “design as a service (DaaS), manufacturing as a service (MFGaaS), experimentation as a service (EaaS), simulation as a service (SIMaaS), management as a service (MANaaS), maintain as a service (MAaaS), integration as a service (INTaaS)”. The authors implement such a CM system as a prototype for evaluation and discussion.

Moghaddam et al. \[175\] present the development of MaaS and its relationship to the concepts of CM, Cloud Based Design and Manufacture (CBDM) and others. The authors propose SoftDiss \[221\] as an implementation platform for CM systems.

Van Moergestel et al. \[255\] analyse the requirements for and propose an architecture for a manufacturing system that enables low-volume and low-cost manufacturing. The authors identify customer requirements for low-volume and flexible production of products as a driver for the development of the CM concept or other MaaS implementations. The architecture relies on cheap reconfigurable production machines (equiplet). For the implementation of the system the authors utilise open source software like Tomcat and have a strong focus on the end-user integration via Web technology.

Sanderson et al. \[216\] present a case study on distributed manufacturing systems which the authors call collective adaptive systems (CAS). The example in their case study is a manufacturing plant by Siemens in the UK which is part of the “Digital Factory” division. The authors present the division, structure and features of the company which is compared to CAS features. Among the identified challenges the authors list, physical layouting, resource flow through supply chains and hierarchical distributed decision making.

For the integration of MaaS (which is called Fabrication-as-a-Service, FaaS, in this work) into CM, Ren et al. \[206\] analyse the service provider cooperative relationship (CSPR). Such a cooperation of MaaS/FaaS providers within a CM system is essential for the task completion rate and the service utilisation as demonstrated by the authors in an experiment.

Guo \[96\] proposes a system design method for the implementation of CM systems. Within this work the MaaS layer of the CM system is further divided into “product design, process design, purchasing, material preparing, part processing and assembly and marketing process”. In the generalised five-layer architecture for the implementation of CM systems, the MaaS is located in the fifth layer.

Yu and Xu \[203\] propose a cloud-based product configuration system
(PCS) for the implementation within CM systems. Such systems interface with the customer enabling the customer to configure or create products for ordering. Within a CM such a system can be employed to directly prepare objects that can be manufactured directly utilising MaaS capabilities. In the implementation within an enterprise the authors utilise the STEP file format for information exchange.

6.7.2. Design-as-a-Service

Besides physical and computational resources that are exposed and utilized as services the concept of CM allows for and requires traditional services to be integrated. Such a service is for example the design of an object, which is traditionally either acquired as a service from a third-party company or rendered in-house.

As with the physical Manufacturing-as-a-Service the service rendered here must be well-defined and abstract. The service in this section is that of the design for AM or traditional manufacturing.

This paradigm can lead to increased involvement of the user as described by Wu et al. [279]. The authors provide an introduction to social product development - a new product development paradigm rooted in Web 2.0 and social media technology. They conducted a study on their students in a graduate level course on product development. They structure the process in four phases beginning with acquisition of user requirement through social media. With the social product development process (PDP) the product development involves the users or customers more directly and more frequently than with traditional PDP. This increased degree of integration requires support through technology which is provided by social media and Web 2.0 technology for communication and management.

Unfortunately the scientific literature on DaaS is sparse and mostly only mentioned as part of architectural or systematic descriptions or implementations of CM systems. In Tao et al. [237] the authors place DaaS among other capabilities services that are part of the CM layer. Other capabilities services are Manufacturing, Experimentation, Simulation, Management, Maintenance and Integration-as-a-Service. In Adamson et al. [12] the same classification is used (but without the Integration and Maintenance, and a combination of the Simulation and Experimentation service). The authors also briefly review literature in the domain of collaborative design for CM systems. In Yu et al. [292] DaaS is also identified as a capability of CM systems and part of its layered structure.
Johanson et al. [121] discuss the requirements and implications of distributed collaborative engineering or design services. According to the authors the service orientation of design and its collaborative aspects will render enterprise more competitive due to reduced costs for software, decreased design times and innovative design. Furthermore, such services promote tighter integration and cooperation with customers.

Laili et al. [141] propose an algorithm for a more efficient scheduling of collaborative design tasks within CM systems. As collaborative design task scheduling is NP-hard, the authors propose a heuristic energy adaptive immune genetic algorithm (EAIGA). In an experiment the authors prove that their implementation is more stable with higher quality results than compared to an genetic algorithm (GA) and a immune GA (IGA).

Duan et al. [66] explore the servitization of capabilities and technologies in CC scenarios. The authors explore and discuss a variety of service offerings as described in literature. Among the identified as-a-Service offerings is Design-as-a-Service which is referenced to Tsai et al. [246]. Duan et al. provide a large collection of “aaS” literature. Contrary to the indication by Duan et al. the work of Tsai et al. does not cover DaaS. It however covers the architectural design of CC systems and service provisioning as well as an analysis of potential drawbacks and limitations of CC systems.

6.7.3. Testing-as-a-Service

Similar to the Design as a-Service (See Sect. 6.7.2) this exposition of a capability as a service can play an important role within CM systems. In general the QA for AM is not sufficiently researched and conducted as the traceability of information from the original CAD model to the manufactured part is insufficient due to the number of conversion steps, file formats and systems involved.

Albeit mentioned in a number of publications on the design and implementation of CM architectures, designs or systems, e.g., Ren et al. [205] or Gao et al. [82], the research on Testing-as-a-Service (TaaS) in CM systems is sparse and the authors are not aware of any dedicated works on this topic.

In contrast, TaaS as a concept for software testing in the cloud is researched by a number of authors, see e.g., Gao et al. [81] or Mishra and Tripathi [173] for an introductory overview, Yan et al. [285] for the special application of load testing, Tsai et al. [245] for service design or Llamas et al. [157] for a software implementation.

Extrapolating from the benefits that TaaS brings to software quality,
e.g., transparency, scalability, concurrency, cost-reduction and certification by third parties, research on this area in CM scenarios is warranted. In contrast to software QA, physical testing has an extended set of requirements and limitations, e.g., object under test must be physically available, higher likelihood that standardised test protocols exist, inability to scale without hardware investment or inability to scale beyond minimum time required for testing. With this section we want to motivate further discussion and research into this area.

6.8. Rapid Technology

As an umbrella term in accordance to the definition “General term to describe all process chains that manufacture parts using additive fabrication processes.” by [4] we examine the relevance of this technology for CM with this chapter. This technology is integral to the product development especially with its sub-technology that is RP (See Sect. 6.8.3). This and the following sections extend on the definitions provided in Sect. 2 by examples and research findings.

For a brief introduction we refer to the following articles. Li et al. [151] propose a method for rapid new product ramp-up within large multi-national companies relying on disperse supply chain networks and out-sourcing partners. In this work the authors consider large-volume product development. For the conceptual framework the authors identified critical members and defined a ramp-up process as a flowchart.

Mavri [165] describes 3D printing itself as a rapid technology and analyses the impact of this technology on the production chain. The author performs an analysis on the influences on the phases of product design, production planning, product manufacturing as well as the topics material utilisation, inventory and retail market. The findings of the author include that AM enables companies to act more agile, cater for smaller markets, limit potential inventory issues and can sustain smaller and slimmer supply chain networks.

Muiita et al. [180] discuss the evolution of rapid production technologies and its implications for businesses. The authors investigate business models and processes, transitions as well as materials and logistics. A decomposition of rapid technology into the phases or layers (Rapid Prototyping, 3D Printing, Rapid Tooling, Rapid Product Development and Rapid Manufacturing) is provided and discussed. The authors recommend the adaption of AM by all companies.
In the book by Bertsche and Bullinger [27] the authors present the work of a research project on RP and the various problems addressed within the topic of Rapid Product Development (RPD). One aspect of this research is the development and integration of systems to efficiently store and retrieve information required throughout the process. Information required in the process is knowledge on construction, quality, manufacturing, cost and time.

In Lachmayer et al. [140] the authors present current topics of AM and its application in the industry. In the chapter by Zghair [295] the concept of rapid repair is discussed. This concept is intended to prolong the life-time of high-investment parts as well as modification of parts in academic settings. The authors perform an experiment for this approach with three objects and conclude that there is no visible difference between additional object geometry in the case of previously SLM manufactured objects. Differences are visually detectable for cast objects that are repaired.

6.8.1. Rapid Tooling

The use case of RT for AM is that the required tools or moulds for the (mass-) production of other parts or objects is supported by provisioning of said tools or moulds. See the definitions of RT in Sect. 2.1.5. RT as a concept is researched and applied for at least 26 years [212]. Conceptually little has changed since the early publications but the number of available AM technologies, materials and support by other concepts like CC has increased. Since its start the idea of RT is to create tools or tooling directly from CAD models thus saving time and material. In this section we present articles from this research to give an overview to the reader and present its relevance and relationship to the concept of CM.

In the review by Boparai et al. [31] the authors thoroughly analyse the development of RT using FDM technology. FDM manufactured objects commonly require post-processing for higher-quality surfaces which is discussed by the authors in a separate section of their work. The authors present a variety of applications of RT with FDM which include casting and injection moulds and scaffolds for tissue engineering. Furthermore, the authors discuss material selection and manufacturing, as well as testing and inspection.

The review by Levy et al. [150] on RT and RM for layer oriented AM from 2003 already states that AM is not just for RP anymore. According to the definition of RT by the authors tools are supposed to last a few thousand to millions applications. The authors focus mainly on plastic injection moulds for tooling and survey a large number of different technologies and materials.
Similarly, the definition of RT by King and Tansey \cite{135}, is focused on injection moulds, a definition that has since been expanded to other tooling areas. In this work the authors present research on material selection for SLS manufactured moulds. In this work the authors analyse RapidSteel and copper polyamide for the use in time-critical RT scenarios.

Lušić et al. \cite{161} present a study on the applicability of FDM manufactured moulds for carbon fibre reinforced plastic (CFRP) objects. The authors achieved up to 84% material saving or 47% time saving for optimised structures compared to a solid mould at a comparable stiffness. The authors experimented with varying shell thicknesses and infill patterns.

Nagel et al. \cite{184} present the industrial application of RT in a company. The authors present at a high level the benefits and thoughts leading to the creation of flexible grippers for industrial robots utilising 3D printing. The authors also present a browser based design tool for the creation of the individual grippers with which the company is able to reduce the time required for product design by 97%.

Chua et al. \cite{56} present a thorough introduction to RT as well as a classification into soft- and hard tooling, with a further divide into direct soft tooling, indirect soft tooling, direct hard tooling and indirect hard tooling. Among the benefits of RT the authors see time and cost savings as well as profit enhancements. The authors discuss each of the classifications with examples and the relevant literature. Examples from industry given support the benefits proposed by the authors.

Rajaguru et al. \cite{201} propose a method for the creation of RT moulds for the production of low-volume plastic parts. With this indirect tooling method, the authors are able to produce low-cost moulds in less than 48 hours. The authors present an experiment where the mould is used for 600 repetitions. The method uses electroless plating of nickel and phosphorous alloy for the micro-pattern moulds.

In the introduction to RT, Equbal et al. \cite{70} start with the basics of various AM technologies. The authors provide a classification schema for RT and discuss each class with the appropriate examples. According to the authors, RT is a key technology for globally active companies in respect to flexibility and competitiveness.

In the review by Malik et al. \cite{162} the authors investigate the use of 3D printing in the field of surgery. The authors discuss the fabrication of medical models for education and operation planning as well as drill-guides and templates as RT technology. In contrast, the direct fabrication of implants
or prosthetics as described by the authors is regarded RM.

6.8.2. Rapid Manufacturing

In contrast to RP the goal of RM is the creation of parts and objects directly usable as end-products or part of end-products (See Sect. 2.1.4). To achieve this usability the requirements on the quality of the parts is higher, therefore the quality control and quality assurance are stricter.

Hopkinson and Dickens [107] provides findings on cost analysis for the manufacturing of parts for traditional manufacturing and AM. The authors identify the current and potential future benefits for RM as the ability to manufacture with less lead time, increased geometric freedom, manufacture in distributed environments and potentially the use of graded material for production. The authors compared the costs incurred for the creation of two objects with injection moulding (IM), SLA, FDM and SLS. For IM the tool costs are high (27360 and 32100 Euro) whereas the unit costs are low (0.23 and 0.21 Euro). In their calculation the equilibrium for the cost of IM and SLS for one of the objects is at about 14000 units and for the other part at around 600 units. This finding validates RM for certain low-volume production scenarios.

Ruffo et al. [211] also present a cost estimation analysis and is an extension and update to the previous work. The authors calculated with a much lower utilisation of the machines (57% compared to 90%), higher labour cost as well as production and administrative overhead costs. Furthermore, the authors took other indirect costs like floor/building costs and software costs into consideration. The authors calculated a higher unit cost for the object (3.25 Euro compared to 2.20 Euro), and a non-linear costing function due to partial low-utilisation of the printing resources which is due to incomplete rows for unit counts not equal or multiple of maximum unit packing. The comparison of these two works illustrates the necessity to use the most up-to-date and complete models for costing estimation.

Ituarte et al. [117] propose a methodology to characterise and assess AM technologies, here SLS, SLA and Polyjet. The methodology proposed is an experimental design for process parameter selection for object fabrication. The authors find that surface quality is the hardest quality to achieve with AM and might not suffice for RM usage with strict requirements. Such an analysis is of value in order to assess the feasibility of certain manufacturing methods in RM scenarios.

In the review by Karunakaran et al. [125], the authors survey and classify
technologies capable of manufacturing metallic objects for RM. The technologies surveyed are CNC-machining, laminated manufacturing, powder bed processes, deposition processes, hybrid processes and rapid casting. The authors develop different classification schemes for RM processes based on various criteria, e.g., material or application. Furthermore, the authors compile a list of RM process capabilities to be used for the selection of appropriate RM processes.

Simhambhatla and Karunakaran [222] survey build strategies for metallic objects for RM. The authors focus on the issues of overhangs and undercut structures in metallic AM. The work concludes with a comparative study on the fabrication of a part using CNC-machining and a hybrid layered manufacturing (HLM) method. With the hybrid approach the authors build the part in 177 minutes compared to 331 minutes at a cost of 13.83 Euro compared to 24.32 Euro.

Hasan et al. [101] present an analysis of the implications of RM on the supply chain from a business perspective. For this study the authors interviewed 10 business representatives and 6 RP or RM service providers. The authors propose both reverse-auctioning as well as e-cataloguing as modes for business transactions.

With rapid changing production the need arises for rapid fixture design and fabrication for the RM provider itself. This issue is discussed by Nelaturi et al. [186], as they propose a mechanism to synthesise fixture designs. The method analyses the models to be manufactured and supported by fixtures as STL files for possible fixture application areas. The algorithm furthermore calculates possible fixture positions and inflicting forces. The authors select existing fixtures from in-house or online catalogues of fixtures for application.

Gupta et al. [98] propose an adaptive method to slice model files of heterogeneous objects for the use with RM. For this the authors decompose the slicing process into three phases (Slicing set up, Slices generation and Retrieving data). The work also surveys other existing slicing techniques for various optimisation goals, e.g., quality, computing resources or part manufacturing time. For the extraction of geometric and material information the authors utilise a relational database for efficient storage. The authors find that utilising the appropriate slicing technique the fabrication time can be reduced by up to 37%.

Hernández et al. [103] present the KTRM (Knowledge Transfer of Rapid Manufacturing) initiative which is created to improve training and knowledge transfer regarding RM in the European Union. For the requirement analysis
of such a project, the authors conducted a study with 136 participants of which the majority (70 %) are SMEs. Such training initiatives are beneficial to the growth in application and increased process majority as the authors find that the knowledge of RM is low but the perceived benefits of this technology include higher quality parts, lower time to markets and increased competitiveness.

With the chapter by Paul et al. [191], the authors provide a thorough overview over laser-based RM. The authors discuss classifications of such systems as well as composition of these systems in general. Process parameters are presented and located in literature. Furthermore, the authors discuss materials available for this class of RM and applications. This work is a comprehensive overview, covering all relevant aspects of the technology, including monitoring and process control.

6.8.3. Rapid Prototyping

Following the definitions in Sect. 2.1.3 Rapid Prototyping (RP) is the concept to speed-up the creation of prototypes in product development. These prototypes can be functional, visual, geared towards user-experience or of any other sort. RP was one of the first uses for AM and oftentimes the terms AM and RP are used synonymously. The quick or rapid creation of prototypes does not necessarily mean fast in absolute terms but rather a more rapid way to create prototypes than traditionally created using skilled or expert labour (e.g., wooden models created by carpenters) or subtractive or formative manufacturing methods oftentimes requiring specialised tooling or moulds.

Pham and Gault [196] provide an overview of commonly used methods to rapidly create prototypes with information on the achievable accuracy, speed and incurred costs of each technology from a very early perspective. A number of technologies, e.g., Beam Interference Solidification (BIS), has since been disused. The accuracy for Fused Deposition Modeling (FDM) stated with 127 µm has not been improved significantly since then.

Masood [163] reviews the technology of FDM and examines the usability of it for RP. Among the advantages of this technology is “Simplicity, Safety, and Ease of Use” as well as “Variety of Engineering Polymers” which makes it suitable for the creation of functional prototypes. A number of limitations, like “Surface Finish and Accuracy”, can diminish the suitability of this technology for certain aspects of prototyping.

In their keynote paper Kruth et al. [137] survey the technologies used for
RP and produce examples for the technologies. Furthermore, they briefly explain the developmental bridge from RP to RT and RM.

The authors Yan et al. [286] present the historical development of RP from its roots in the analogue and manual creation of prototypes to digital fabrication methods. The also present a list of current limitations for digital RP. Among the five limitations they place high-manufacturing cost, for the manufacturing resources, and the insufficient forming precision. The first argument of cost is often put forward in its reversed statement as RP is proposed as a low-cost production method, when compared to traditional prototyping.

Azari and Nikzad [21] present a review on RP in dentistry with a distinction of models in dentistry and its general meaning. They discuss the problems in data-capture for RP due to the nature of living patients. They further discuss the use of AM for drill-guides which is an application for RT.

Liu et al. [155] present a study on profit mechanisms associated with cloud 3D printing platforms predominantly in China. They argue that such services can enable small and medium sized enterprises (SME) to produce prototypes more rapidly and cheaper thus increasing their competitiveness.

Roller et al. [209] introduce the concept of Active Semantic Networks (ASN) as shared database systems for the storage of information for the product development process.

6.9. Design

In traditional (subtractive or formative) manufacturing the design is driven by the capabilities provided by the manufacturing equipment. This is described as Design for Manufacturing or Design for Manufacturability (DFM) which means that the parts designed must be easy and cheap to manufacture. Especially in large volume production the parts must be machinable in a simple way as tooling, tool changes and complex operations are expensive. Furthermore, with traditional manufacturing certain operations like hollowed or meshed structures are not possible to produce or incur large costs. With AM the design of objects or parts is not strictly limited by these considerations as flexibility comes for free and a number of operations (e.g., intersecting parts, hollowed structures) become possible. The designer can chose more freely from available designs and is less restricted. The design itself can concentrate on the functionality of the part, rather than its manufacturability.
In the review by Rosen [210], the author proposes principles that are relevant for design for AM (DFAM) as they exist in literature. The suitability of AM is declared for parts of high complexity and low production volume, high production volume and high degree of customisation, parts with complex or custom geometries or parts with specialised properties or characteristics. Within this review the author proposes a prototypical design process for AM that is derived from a European Union standardisation project by the name of SASAM [67].

Kerbrat et al. [129] propose a multi-material hybrid design method for the combination of traditional manufacturing and AM. For this method the object is decomposed based on the machining difficulty. The authors implemented their method in a CAD System (Dassault Systems SolidWorks [68]) for evaluation. This hybrid design method is not limited to a specific AM or manufacturing technology. The authors omit information on how the decomposed part or parts are fused together and how to compensate for inaccuracies within the manufacturing process.

Throughout the design process and later for manufacturing it is necessary to convey and transport information on design decisions and other specifications. Brecher et al. [38] provide an analysis of the STEP [8] and STEP-NC [2] file formats. This analysis is used to propose extensions necessary for the use in an interconnected CAD-CAM-NC (CAx) platform.

Buckner and Love [41] provide a brief presentation of their work on the automatic object creation using Multi-Objective Constrained Evolutionary Optimisation (MOCEO) on a high-performance computing (HPC) system. With their software, utilising Matlab [69] and driving SolidWorks, the objects are created automatically following a given set of restrictions and rules.

Cai et al. [43] propose a design method for the personalisation of products in AM. Their work defines basic concepts ranging from Design Intent to Consistency Models. The design method is intended to convey design intentions from users or designers in a collaborative design or CAD environment.

Vayre et al. [257] propose a design method for AM with a focus on the constraints and capabilities. This design method consists of four steps (Initial Shape Design, Parameter Definition, Parametric Optimisation, Shape
Validation). For the initial shape design, the authors propose the use of topological optimisation. The authors illustrate this process with an example of the re-design of an aluminium alloy square bracket.

Diegel et al. [60] discuss the value of AM for a sustainable product design. The authors explore the benefits (e.g., Mass customisation, freedom of design) and design considerations or restrictions for AM (e.g., surface finish, strength and flexibility). The authors argue that AM offers create potential for the creation of long-lasting, high-quality objects and parts that can save resources throughout their lifetime by optimised design.

Ding et al. [63] analyse existing slicing strategies for the creation of objects with AM. Besides the analysis, the authors propose a strategy to create multi-directional slicing paths to be used with AM machines that support multi-axis deposition or fabrication. By the authors’ analysis the existing software for slice creation is insufficient and leaves uncovered areas (hole or gap). This work is not on the design for AM but rather on the design of the resulting machine-paths for the manufacture with AM fabricators.

In Wu et al. [274] the authors discuss the concept of Cloud-Based Design and Manufacturing (CBDM, see also [278]) in which the whole design and manufacturing process chain is executed in a cloud environment. CBDM is an extension to the CM concept as it expands the process chain horizontally into the collaborative and cooperative domain of the cloud. CBDM utilises Web 2.0 technology, service-oriented architecture (SOA) concepts, semantic web technologies and has an inherent connection to social networking applications. In this article concepts like collaboration, cooperation and crowdsourcing for design for AM are discussed and exemplified.

### 6.10. Additive Manufacturing

We see AM an integral component in CM and Industry 4.0 settings due to the benefits it provides. Among those benefits are flexibility, resource efficiency and the freedom in and of design. In this section we survey scientific literature regarding AM, especially works that provide an overview (e.g., reviews, surveys), present important aspects or exhibit common characteristics of this domain.

Le Bourhis et al. [35] develop the concept of design for sustainable AM (DFSAM) to minimise the yet unknown environmental impact of AM. According to the authors about 41 % of the total energy consumption globally is attributed to industry. The authors further provide a division for the French industry in 2010 where about 12 % percent are attributed to manufacturing.
The authors claim that AM can reduce the energy required as it limits waste material. The authors experiment on the energy and resource consumption of the Additive Laser Manufacturing (ALM) process and present a method to calculate electricity, powder and gas consumption for an object based on the respective GCode.

In their work Kim et al. [134] present a federated information systems architecture for AM. This architecture is intended to facilitate an end-to-end digital implementation of AM, i.e., “digital thread”, design-to-product process. The authors analyse, for each phase (Part geometry/design, Raw/tessellated data, Tessellated 3D model, Build file, Machine data, Fabricated Part, Finished Part, Validated Part) the available and used data formats and supporting software. The focus of their conceptual architecture is interoperability by an open architecture.

Balogun et al. [23] perform an experiment on the electricity consumption of the FDM process. The authors divide the manufacturing process into its components (Start-up, warm-up, ready-state, build-state). In an experiment they analyse three different FDM machines (Stratasys Dimension SST FDM, Dentford Inspire D290 and PP3DP) for their power consumption profile during manufacturing. The machines differ significantly in the energy demand with the Dentford machine requiring 1418 Wh and the PP3DP only requiring 66 Wh. Furthermore, the authors compare the energy consumption and manufacturing duration of a FDM machine to a milling machine. In the experiment the AM process consumed 685 Wh and the Mikron HSM 400 milling machine only 114 Wh. The AM cycle time was 3012 s (without 3600 s for support structure removal in an ultrasonic cleaning tank) and the milling machine cycle time was 137 s.

Weller et al. [268] discuss the implications of AM on the company and industry level. Economic characteristics, i.e., opportunities like acceleration and possible price premiums, lower market entry barriers and limitations like missing economy of scale, missing quality standards are discussed in this analysis. The authors perform modelling of various scenarios and propositions for the market under the influence of AM. Their prediction for first adoption is within markets with an overall lower economy of scale.

Efthymiou et al. [67] present a systematic survey on the complexity in manufacturing systems. Albeit not directly referencing AM this study is relevant to understand the implications of AM on manufacturing systems.

Turner et al. [248] survey melt extrusion AM processes. This work is part of a two piece series (See also [247]) with this part focusing on the design
and process modelling. The authors provide a short market analysis in their introduction. The authors discuss literature relating to various processing steps and problems, e.g., die swelling, with melt extrusion processes. The authors provide a thorough overview on the literature for this topic.

Mitev [174] approaches the topic of AM in a very uncommon manner, namely with a philosophical approach. This is the sole publication with this approach found by the authors. The author discusses AM for the question on what matter is and how 3D printing affects our concept of matter and material.

In contrast to the previous author, Bayley et al. [25] present a model for the understanding of error generation in FDM. This work consists of two parts with experiments. The first part analyses actual errors in FDM manufactured parts (e.g., Roundness error, geometrical deviation). In the second part the authors construct a framework for error characterisation and quantification.

In the review by Kai et al. [123] the authors evaluate the relationship of manufacturing systems and AM briefly. The authors also provide an overview over one possible decomposition of AM and its academic relevance through numbers of published works from 1975 to 2015.

6.11. Cloud Computing

Cloud Computing (CC) is the concept of virtualized computing resources available to consumers and professionals as consumable services without physical restraints. Computing, storage and other related tasks are performed in a ubiquitous cloud which delivers all these capabilities through easy to use and interface front-ends or APIs. These concepts enable enterprises to acquire computing capacities as required while, often paying only for the resources consumed (Pay-as-you-go) in contrast to payment for equipment and resources in stock (e.g., leasing, renting or acquisition). Concepts developed for this computing paradigm are of importance for the CM domain, as many problems stated or solved are interchangeable within domains. What CC is to computing resources (e.g., storage, computing, analysis, databases) CM is to physical manufacturing resources (e.g., Tools, 3D printer, drills).

In the definition of Cloud Computing, Mell and Grance [171] from NIST develop and present the characteristics and services models for CC.

Truong and Dustdar [244] present a service for estimating and monitoring costs for cloud resources from the domain of scientific computing. This model is also suitable for the monitoring of costs in other cloud based computing
scenarios as CM with adaptions. The authors present an experiment where they analyse the cost of scientific workflows on with on-premise execution and deployment to the Amazon Web Service (AWS) cloud system.

Stanik et al. [228] propose the cloud layer that is Hardware-as-a-Service for the remote integration of distinct hardware resource into the cloud. The authors argue from the point of embedded systems development and testing but the concepts described are universally applicable for any hardware that is intended to be exposed as a service.

Mehrsai et al. [168] propose a cloud based framework for the integration of supply networks (SN) for manufacturing. The authors discuss the basics of supply networks and CC in order to develop a concept to integrate CC for the improvement of SNs. This modular approach is demonstrated in an experimental simulation.

Oliveira et al. [187] research the factors influencing the adoption of CC in general and for the manufacturing sector. The authors test their hypothesis on a survey of 369 companies from Portugal with 37.94 % of the companies from the domain of manufacturing. The authors find that security concerns do not inhibit the adoption of CC in the manufacturing domain sub-sample of their survey group.

Ramisetty et al. [202] propose an ontology based architecture for the integration of CC or cloud platforms in advanced manufacturing. The authors claim that adoption of CC in manufacturing is less than in comparable industries due to the lack of social or collaborative engagement. The authors implement three services (Ontology, Resource Brokering and Accounting) for an evaluation in the WheelSim App. The authors propose an “App Marketplace” for manufacturing services to further the adoption of CC in the manufacturing industry.

Um et al. [250] analyse the benefit of CC on the supply chain interactions in the aerospace industry. The authors propose a manufacturing network for contracting and subcontracting based on CC. In this architecture the basis for information exchange is the STEP-NC file format.

Valilai and Houshmand [254] propose a service oriented distributed manufacturing system on the basis of CC. For their work the authors analyse the requirements and basics of globally distributed manufacturing systems. The proposed system (XMLAYMOD) utilises the STEP file format for the information exchange and enables a collaborative and distributed product development process as well as process planning and execution.
6.11.1. Internet of Things

Internet of Things (IoT) is a term used to describe a network consisting of physical objects connected to the Internet. These physical objects can be tools, parts, machines, actuators or sensors. The concept of IoT is integral to the CM paradigm as it is necessary to control the AM resources transparently and monitor the resources for efficient utilisation planning and scheduling. In IoT scenarios the use of open-standards helps to avoid vendor lock-in.

Tao et al. [234] present a very high-level description of the possible integration of IoT in CM scenarios. In four proposed layers (IoT, Service, Application, Bottom Support) of CM systems, they declare IoT and the corresponding layer as core enabling technology.

Tao et al. [238] propose a five layer (Resource layer, perception layer, network layer, service layer and application layer) architecture for a CM system. The authors propose the utilisation of IoT technology as a method to interface the manufacturing resources into the architecture. This work is very similar to [234].

Qu et al. [200] present a case study on the integration of CM and IoT technology into an enterprise to synchronise the production logistics (PL) processes. For the implementation they propose a five tier (Physical resource layer, Smart object layer, Cloud manufacturing resource management layer, Cloud manufacturing core service layer, Cloud manufacturing application layer) decomposition. The system uses AUTOM [299] as a backbone for the IoT integration.

Baumann et al. [24] propose the development of flexible sensor boards for the use in the monitoring of AM processes. The authors analyse existing sensors available and provide an architectural overview over a system for the incorporation of these sensor boards into a manufacturing control and monitoring system. With these sensors AM resources can be bridged to control systems or services thus enabling IoT functionality for the resources.

Caputo et al. [46] perform a review on IoT from a managerial perspective with the application of AM. The authors develop a four staged (Radical, Modular, Architectural and Incremental) conceptual framework to classify innovation and research on the topic. Within this framework’s description AM resource will become digitally represented by sensors and IoT technology.

In the review by Kang et al. [124], the authors focus on global research on smart manufacturing and its enabling technologies and underlying concepts. In the section on IoT the authors link this concept to other technologies like
SoA, CM and smart sensors.

Vukovic [259] discusses the importance of APIs for the IoT deployment and usage. The author discusses the common architectural patterns in IoT scenarios and the arising requirement for APIs to further this technology.

In the work by Kubler et al. [138], the authors discuss the evolution of manufacturing paradigms and the origins of CM along its relationship with IoT technology. The authors conclude that CM is not widely adopted because of security concerns but research in AM and IoT will drive CM forward.

6.11.2. Cyber-physical Systems

Cyber-physical Systems (CPS) are one of the key enabling technologies for the Internet of Things. CPS is a term coined by the NSF (National Science Foundation) to describe systems, e.g., machines, parts or tools that have capabilities to sense and interact with their physical environment while being connected to the Internet in order to relay state and environment information to an Internet based control system. The first occurrence in scientific literature can be found in Lee [147]. In the domain of 3D Printing, AM and CM such systems are required to enable seamless integration of systems. With CPS, it is possible for an AM hardware resource to signal its current status or utilisation to a centralised or cloud-based control infrastructure in order to participate in scheduling endeavours and become part of a controllable system.

In the work by Chen and Tsai [51] the authors propose the concept of ubiquitous manufacturing. This concept is similar to CM but with a stronger focus on mobility of users and manufacturing resources. For this concept ubiquitous sensor and IoT technology are key enabling technologies.

Lee et al. [148] propose a five layer architecture for CM based on IoT technology. The layers in this architecture are from bottom to top: Smart Connection Layer, Data-to-Information Conversion Layer, Cyber Layer, Cognition Layer and Configuration Layer. The goal of this work is to provide a guideline for implementation of such a CPS backed manufacturing systems and to improve the product quality as well as the system’s reliability.

Sha et al. [218] provide a general introduction into CPS and the related research challenges. The authors identify QoS composition, knowledge engineering, robustness and real-time system abstraction as the four main research questions for this technology.

In the survey by Khaitan and McCalley [130] the authors study the design, development and application of CPS. In the list of identified application
scenarios (Surveillance, Networking Systems, Electric Power Grid and Energy Systems, Data Centres, Social Networks and Gaming, Power and Thermal Management, Smart Homes, Medical and Health Care, Vehicular and Transportation Systems) manufacturing systems are missing. Despite this lack of mention, application in e.g., transportation and power management is relevant for CM systems.

Kuehnle [139] proposes a theory of decomposition for manufacturing resources in distributed manufacturing (DM) systems. DM is similar in concept to CM in relation to the decomposition of manufacturing resources in vitalised services. According to the author IoT technology and CPS are among the enabling technologies for this smart manufacturing concept.

Yao and Lin [289] expand the concept of CPS into socio-cyber-physical-systems (SCPS) with this study on smart manufacturing. This extension to social aspects of manufacturing (e.g., collaboration and cooperation) is expected to be an integral part of the next industrial revolution (Industry 4.0).

Turner et al. [249] discuss the risk of attacks and their implications on CPS in the domain of manufacturing. The authors present a number of attack vectors, e.g., attack on the QA process and counter or mitigation strategies. According to the authors CPS provide an additional attack surface for malicious third parties.

6.12. Scheduling

In CM as in CC a number of resources must be provisioned on demand. In contrast to CC the requirements for the execution resource can be more complex than just a computing resource. With CM manufacturing resources must first be described in an abstract way (See Sect. 6.13) to be schedulable. In this section we present current research on the challenges that come from scheduling.

Cheng et al. [53] introduce the concept of CM in their work and perform a brief review over possible criteria for scheduling in such scenarios. The authors provide four scheduling modes based on the three identified stakeholders (Operator, Consumer and Provider) and the system as a whole. The proposed modes consider energy consumption, cost and risk. The proposed system-centred cooperative scheduling mode yields the highest utilisation in their experiment.

Liu et al. [156] propose a scheduling method for CM systems for multiple enterprise and services scenarios. The authors use the criteria time, cost and
pass-rate for the task selection. Based on these criteria constraints are con-
structed for the decomposition of tasks into subtasks and their distribution
onto resources. The authors take geographical distance, respectively delivery
times between CM locations into consideration. Their simulation concludes
that for a 50 task scenario, with 10 enterprises offering 10 services in to-
tal, the utilisation is 49.88 % compared to 10 tasks (17.07 %). The authors
provide no specific scheduling solution with their work.

Laili et al. [142] define the problem of optimal allocation of resources based
on a 3-tier model (Manufacturing Task Level, Virtual Resource Layer and
Computing Resource Layer). The authors prove that the optimum resource
allocation is NP-complete. For the reason of NP-completeness of the schedul-
ing problem this and other authors propose heuristics based algorithms to
provide near-optimal scheduling. Heuristics based scheduling algorithms pro-
vide near-optimum solutions for most of the scheduling instances without the
guarantee to achieve an optimum solution but at greater speed than exact
computation. In this work the authors propose a heuristic algorithm in-
spired by the immune system (Immune Algorithm, IA). In an experiment
they compare their algorithm against three other heuristic algorithms and it
performed comparable.

Wang [261] proposes a web-based distributed process planning (Web-
DPP) system that performs process planning, machining job dispatching
and job execution monitoring. The system is implemented as a prototype
and connects to legacy machine controllers. The proposed system acts di-
rectly on the manufacturing resource and interfaces with the Wise-ShopFloor
framework [262]. The author does not provide information on scheduling al-
gorithms or methods used.

Huang et al. [114] propose a scheduling algorithm based on Ant Colony
Optimisation (ACO). In an experiment they compare the algorithm with
and without a serial schedule generation scheme (SSGS) against another
heuristic Genetic Algorithm (GA). Their algorithm for conflict resolution
performs faster and with better quality results than the GA when used with
the SSGS.

Lartigau et al. [144] present an 11-step framework for scheduling and order
decomposition within a CM system. This scheduling is deadline oriented
and implemented in a company environment for evaluation. The paper lacks
validation and conclusive results for the proposed algorithm.

In the work by Zhang et al. [300] the authors propose a queue optimisation
algorithm for the criteria lowest cost, fastest finished time, cleanest environ-
ment and highest quality. The proposed CM system relies on active and real-
time environment and machine-status sensing through heterogeneous sensors.
Furthermore, they utilise semantic web (Ontology) technology for the system.
Cao et al. [45] refine an ACO algorithm for efficient scheduling within
a CM. This algorithm optimises for time, quality, service or cost (TQSC).
With the addition of a selection mechanism to ACO their ACOS algorithm
performs with better quality results and faster convergence in comparison to
Particle Swarm Optimisation (PSO), GA and Chaos Optimisation (CO).
Jian and Wang [120] propose an adapted PSO algorithm (Improved Coop-
erative Particle Swarm Optimisation, ICPSO) for the use in batch processing
within a CM system. Batch tasks are indivisible units of work to be executed
with manufacturing resources. The authors present an experiment for the
comparison of the proposed algorithm with an PSO and a cooperative PSO
scheduling algorithm in respect to the cost and time criteria. The algorithm
performs better than the other two algorithms.

6.13. Resource Description

For the usage of manufacturing resources within CM there must be an
abstract definition or description of the resources. Open-standards are prefer-
able where available in order to avoid vendor lock in.
Luo et al. [160] propose a six step framework for the description of Man-
ufacturing Capabilities (MC). The representation of this information utilises
ontology and Fuzzy technology. Within the framework the authors represent
information on the manufacturing equipment, computing resources, intellec-
tual resources, software and other resources.
Wang et al. [264] also propose an ontology based representation for man-
facturing resources. The information and ontology is derived from man-
facturing task descriptions. The authors implement their algorithm in an
enterprise setting in a medium-sized Chinese company for evaluation.
As a more general approach to CC scheduling Li et al. [152] propose an
ontology based scheduling algorithm with PSO. The authors motivate their
work by an example in a logistics centre which is relevant to the domain of
CM. For this algorithm the selection is restricted based on the Quality of
Service (QoS) with time, cost, availability and reliability as criteria.
Zhu et al. [302] develop an XML based description for manufacturing
resources oriented at the Web Service Description Language (WSDL) for web-
services. The authors separate the resource description into two parts (Cloud
End, CE and Cloud Manufacturing Platform, CMP). In their approach, they
reflect static data, e.g., physical structure or input data types, in the CE layer whereas the CMP layer reflects the dynamic data, e.g., function parameters.

Wu et al. [282] propose an ontology based capability description for industrial robot (IR) systems. IR are regarded as manufacturing resources and described as such. Besides manufacturing machines such IR systems enable CM to perform as a flexible and agile manufacturing system.

6.14. Hybrid Manufacturing

Hybrid Manufacturing is a term used for the combination of AM and traditional manufacturing methods. The combination of these methods promises to provide benefits from both, e.g., speed and accuracy of a milling machine with the low material input from AM.

Lu et al. [159] propose an architecture for a hybrid manufacturing cloud. Their definition of hybrid refers to cloud operation modes (private, community and public cloud). Besides the architecture they present a cloud management engine (CME) which is implemented for evaluation purposes on Amazon Web Service (AWS).

In the work by Kenne et al. [128] a model for a hybrid manufacturing-remanufacturing system is proposed. The authors refer the term hybrid to manufacturing and remanufacturing in combination. Remanufacturing denotes an alternative use of products at the end of their product lifecycle for value generation. In an experiment the authors calculate the cost for a mixture of parameters, e.g., return rates and come to the conclusion that the system is applicable with customisation to various industries.

In the review by Chu et al. [55] the authors discuss 57 hybrid manufacturing processes. These micro- and nanoscale processes are categorised in three different schemes (concurrent, main/assistive separate and main/main separate). The authors survey a combination of 118 processes in this work.

The review by Zhu et al. [305] provides a classification of hybrid manufacturing processes. The authors present an extensive list of mainly two-process combination manufacturing processes. For this work the authors explore the existing definitions of manufacturing and hybrid manufacturing processes in literature.

In another work by Zhu et al. [304] the authors propose a build time estimation for the iAtractive [303] process that combines additive, subtractive and inspection processes. This process is based on FDM and the build time prediction is based on the same parameters as normal FDM build time prediction. The authors provide a discussion on an experiment for which
their estimation ranged from approximately -12 % – 12 % to the real build time. The authors only provide a build estimation method for the additively manufactured part of the process.

Lauwers et al. [145] propose a definition and classification of hybrid manufacturing processes with their work. They define these processes as acting simultaneously on the same work area or processing zone. This definition excludes processes that combine processing steps sequentially.

Elmoselhy [68] proposes a hybrid lean-agile manufacturing system (HLAMS). The author develops the system for the requirements in the automotive industry. The definition of hybridity in this work refers to the school of thinking for manufacturing.

The work by Kendrick et al. [127] proposes a solution to the problems associated with distributed manufacturing through the utilisation of hybrid manufacturing processes. The authors propose four options for the usage of distributed hybrid manufacturing systems (Local factories, manufacturing shops, community areas, personal fabrication). The described usage of hybrid MS can be further utilised in CM systems.

Yang et al. [287] propose a hybrid system for the integration of multiple manufacturing clouds. The definition of hybridity used in this work refers to the mixture of diverse manufacturing clouds and not on the manufacturing process itself. The architecture proposed links the various clouds together for a single point of interaction integration. The authors define adaptors and a broker system and implement these for evaluation purposes.

In the overview by Zhang et al. [298] the authors use the term hybrid to describe the cloud management. Their definition for the three cloud types used in CM is private/enterprise cloud, public/industry cloud and a mixture of both as hybrid cloud.

6.15. Research Implications

From the provided literature we have identified the following number of open research questions. The listing compiled is non-exhaustive due to the nature of scientific research.

Bourell et al. [3] provide a report on the “Roadmap for Additive Manufacturing” workshop that took place in 2009 and resulted in proposal for research of the coming 10 to 12 years. The recommendations are grouped into 1. Design 2. Process Modelling and Control 3. Materials, Processes and Machines 4. Biomedical Applications 5. Energy and Sustainability Applications 6. Education 7. Development and Community and 8. National Testbed
Center. The recommendations include the proposal to create design methods for aiding designers with AM, creation of closed-loop printing systems and the design and implementation of open-architecture controllers for AM fabricators.

The authors reflect on their proposed roadmap in an article [34] five years later. In this analysis the authors state that the direct influence of the Roadmap is hard to quantify. The authors remark that the report is referenced about 50 times in scientific literature but only one project can be clearly attributed to the Roadmap.

Lan [143] identifies the following four tasks for future research in his review. 1. Combination of Web services and software agents. 2. Collaborative network environment with the focus on integration and interoperability. 3. Focus on Web technology integration in RM systems and 4. Collaborative product commerce and collaborative planning and control.

In the review by Fogliatto et al. [77] on Mass Customisation (MC), the authors identify the following research needs: 1. Research on Rapid Manufacturing (RM) to support MC. 2. Research on the value of MC for consumers as well as environmental, economic and ethic value. 3. Research on Quality Control. 4. Research on Warranty for MC objects and 5. Case Studies and empirical validation.

Khan and Turowski [132] perform a survey on challenges in manufacturing for the evolution to Industry 4.0. The authors identify six current and future challenges which are the following topics: 1. Data integration (IoT, Big-Data, real-time data, data management). 2. Process flexibility (Adaption, Change management). 3. Security (Connectivity, monitoring, compliance). 4. Process integration within and across enterprise boundaries (Integrated processes, logistics, optimisation). 5. Real-time information access on hand-held devices (Web technology, ERP integration) and 6. Predictive Maintenance (Machine data, sensors).

Among the research needs identified by Adamson et al. [11] in their review are the following: 1. Capabilities, information and knowledge integration and sharing as well as cloud architectures. 2. Definitions and standards for CM. 3. Intelligent, flexible and agile, distributed monitoring and control systems. 4. Business models. 5. Intellectual properties and 6. Cost, security and adoption of CM systems. Furthermore, the authors identify and predict: 1. The emergence of cloud service providers. 2. Real world connectivity (IoT). 3. New collaboration and cooperation scenarios (Customer-manufacturer and manufacturing collaboration). 4. Increased competitiveness.
loop manufacturing 6. Manufacturing of feature function blocks 7. Increased awareness and research on sustainable operations.

In the work by Oropallo and Piegl [188] the authors specifically researched and compiled ten challenges in current AM systems that require research. The challenges are 1. Shape optimisation (Cellular structures and topology optimisation) 2. Design for 3D printing (Software support, design methodology) 3. Pre- and Postprocessing (File formats, model preprocessing, part postprocessing) 4. Printing methodologies (Layered manufacturing, voxel and digital material, non-layer oriented methods) 5. Error control (Before and during printing) 6. Multi material printing (Modelling and manufacturing support) 7. Hardware and Maintenance issues (Process and material based issues) 8. Part orientation 9. Slicing (Adaptive and direct slicing) 10. Speed

Wu et al. [274] explicitly identify the following research needs for the evolution of CM 1. Cloud-Based Manufacturing (Modeling and simulation of material flow, concurrency and synchronisation for scalability) 2. Cloud-Based Design (Social media integration and leveraging, CAx convergence and cloud enablement) 3. Information, Communication, and Cyber Security (IoT, Security-as-a-Service) and 4. Business Model.

The work by Huang et al. [115] examines the state of the art of AM and names the following research areas for future investigation: 1. Materials 2. Design (Methods and tools, complex geometries, lifecycle cost analysis) 3. Modeling, Sensing, Control, and Process Innovation (Multi-scale modelling simulation, error and failure detection, optical geometry reconstruction, faster hardware, bioprinting) 4. Characterization and Certification and 5. System Integration and Cyber Implementation (Knowledge management integration, cloud based systems).

7. Summary

This article provides an overview over the topic that is CM and 3D Printing services.

With the overview of the existing definitions (See Sect. 2) and the extension of the definition proposed we create the foundation for the following work.

The review is based on the topological map presented in Sect. 6.1. Concepts, techniques, methods and terminology is presented by exploring different authors work. We perform an explorative extension study to [204] due to relevance for this domain (See Sect. 5). In this study we cover and analyse
48 publicly available services. extension considers APIs of such services a further distinction to be made. This work also gives an overview on available journals in the domain of AM or 3D printing in general as to support other researchers’ in finding suitable audiences for their work. One journal was established 31 years ago and provides a catalogue of over 21000 articles with no exclusivity to AM or 3D Printing. In recent years a number of new journals were established or are currently in the process of being established. Their focus is solely on AM or related domains like bioprinting.

The domain of AM, CM, 3D Printing, RM and related domains is thoroughly presented in this work by means of literature analysis in scientometric sense (See Sect. 1.1.2 and Sect. 1.2).

The results presented in this work illustrate the scientific development of various techniques and methods from these domains in a time period ranging from 2002 to 2016 (See Sect. 6).

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136
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