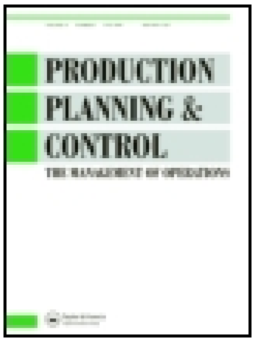

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Additive manufacturing and supply chains – a systematic review

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ABSTRACT
In most supply chains, the application of additive manufacturing (AM) is still far from common. However, various industries ranging from aerospace to consumer goods are investigating its potential to enable the digital value chain. Considering these developments, the research community has supported the adoption of AM in supply chains in many ways. This article contributes to the scientific discourse by systematically reviewing relevant literature depending on industry sector, purpose and supply chain area following the SCOR framework to allow fast access to essential information. The review encompasses 1004 articles, where 141 were subjected to a full-text analysis with argument-specific coding. Findings revealed the predominant AM trends for supply chains, perceived benefits and challenges, and possible applications. Managerial implications based on an overview of (envisioned) applications of AM in different industries are outlined. Additionally, based on a qualitative analysis, gaps in the literature and future lines of research were identified.

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Additive manufacturing; 3D printing; systematic literature review; research gaps; SCOR

Introduction

Additive manufacturing (AM) is the standard term for the process of creating parts by joining materials – layer by layer – directly from 3 D model data (ISO 2020), therefore it is often synonymously referred to as 3 D printing (Gibson, Rosen, and Stucker 2015). In most supply chains (SCs), the application of AM is still far from common (Schniederjans 2017), various industries ranging from aerospace to consumer goods as well as related services (e.g. logistics service providers and shipping companies) are, however, investigating its potential as a key technology to enable the digital value chain (D'Aveni 2015).

The research community has supported the adoption of AM in SCs in a predominantly explorative or isolated way. Rogers, Baricz, and Pawar (2016) explained that most of the scientific literature focuses on mere technical or operational aspects of the manufacturing approach itself. Potential challenges arising from the actual integration within the existing business processes and especially across the SC are often neglected. This article provides quick access to key arguments in the literature with the goal to enhance the knowledge base about AM in SCs. Particularly, the article reviews and characterises main arguments in the literature covering the application of AM in the different areas of SCs. Furthermore, these arguments have been clustered according to key benefits and challenges, thereby identifying various research gaps.

The selected methodology for the same is a systematic literature review organised according to the Supply Chain Operations Reference (SCOR) model (APICS 2017). This approach, that has previously been used in a different context by Chehbi-Gamoura et al. (2020) as well as Kamble, Gunasekaran, and Gawankar (2020), offers researchers and practitioners easy guidance for specific issues at hand and allows the quick identification of potential challenges and benefits in the different areas of the SC related to AM. An industry-specific analysis is also included to allow a straightforward discussion in this regard.

AM and its influence on SCs is a new and emerging field with substantial research activity where several articles have been published reviewing or partially synthesising the corresponding literature. Most notably, Niaki and Nonino (2017) reviewed the literature on the management of AM, Fosso-Wamba (2017) addressed AM supply chain issues with a limited scope, and Ryan et al. (2017) summarised the discussion about future AM supply chain scenarios. Verboeket and Krikke (2019) presented a literature review with the conclusion that AM is mainly used for small, low demand and geometrically complex products. Considering the limitations of existing reviews and the overall research dynamics in the field of AM, there is a clear need for a systematic and holistic review of the impacts of AM on the SC with a focus on distinguishing between related benefits and challenges. This study aims to close this gap and provide an informed guide

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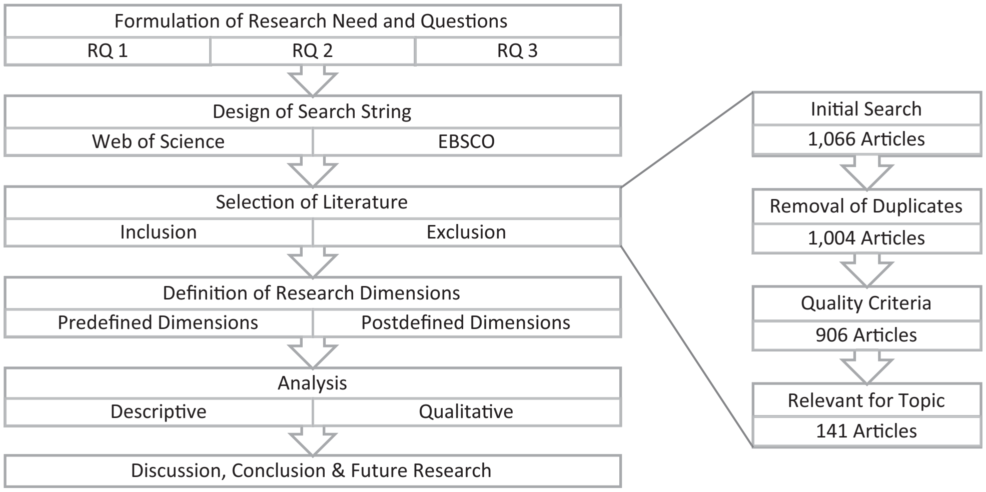

Figure 1. Graphical structure of the review and the literature selection process.

for future research through the identification of potential research streams and questions.

Review design

New or emerging topics generally benefit significantly from a holistic conceptualisation and synthesis of the literature. Contrary to traditional 'narrative' literature reviews, a systematic literature review is a more rigorous and well-defined approach to reviewing the literature in a subject area (Cronin, Ryan, and Coughlan 2008; Tranfield, Denyer, and Smart 2003; Delbufalo 2012). The term 'systematic' in this context hence means transparent, rigorous, and comprehensive (Rutter et al. 2006), and it should follow a pre-defined plan which, in the case of a systematic literature review, is the review protocol (The Cochrane Collaboration 2018). In accordance with Thomé, Scavarda, and Scavarda (2016), Figure 1 briefly explains and summarises the most important elements of the protocol of this systematic literature review.

Research questions

A systematic literature review should be regarded as a self-contained research project as it is commonly used to answer well-focussed research questions (Denyer and Tranfield 2009; Torraco 2016; Hochrein et al. 2015). Following established methodological standards and the exemplary research questions described by Randolph (2009), three research questions for the systematic literature review were defined. Research question 1 (*RQ 1*) is broader and aims at identifying necessary research dimensions for the analysis, while *RQ 2* and *RQ 3* are more specific and aim at clearly identifying research gaps and potentials:

> RQ1: What are the key themes in the literature on the application of AM in the different areas of the supply chain?
>
> RQ2: Which benefits and challenges are identified in the literature concerning the application of AM in the different areas of the supply chain?
>
> RQ3: Which research avenues can be identified for the application of AM in the different areas of the supply chain?

Table 1. Search string used in this systematic literature review.

(additive manufacturing OR 3d printing OR rapid prototyping OR additive techniques OR layer manufacturing OR freeform fabrication)	AND	(supply chain OR value chain OR logistics OR transportation OR operations management)

Literature search

A clear search strategy significantly contributes to the systematic extraction of articles for a literature review. It is important to determine what terms to look for, how to extract the relevant articles, and how to specify the search (Ahlstrom 2016). The focus in this article lies on the impact of AM on SCs so the literature search focussed on articles addressing both issues simultaneously. Synonyms and variations of '*Additive Manufacturing*' (Gibson, Rosen, and Stucker 2015; Gebhardt 2012) and '*Supply Chains*' (Ayers 2006) were combined using Boolean operators (Saunders, Lewis, and Thornhill 2009) to form a search string (see Table 1). '*Operations Management*' was added as a search term to increase the range of results. The initial literature search was performed on two research databases – Business Source Premier and Web of Science – by scanning article titles and abstracts. These databases are widely used for systematic literature searches in supply chain research (see for example Sauer and Seuring (2017), Wankmüller and Reiner (2019), or Delbufalo (2012)) and offer good applicability in regard to the scope of this article as well as the specified inclusion and quality criteria. Two databases were used in order to expand the potential range of articles; the search yielded 1066 articles (as of October 2019).

Selection of the literature

After excluding duplicate articles (62), the authors screened all articles to ascertain whether they meet the necessary criteria for inclusion (see Table 2). To ensure the high academic standards of the publications, all potentially eligible articles had to be published in journals with rankings either in the 'ABS' ranking by Chartered Association of Business Schools (2018), the 'VHB' ranking by German Academic Association

Table 2. Criteria for article inclusion.

Criteria for inclusion	Explanation
A journal ranking of: -VHB ranking greater or equal to 'C' OR -ABS ranking greater or equal to '2' OR -A placement on the SCIE.	Only articles published in high-quality scientific journals were eligible.
Date of publication between 2008 and October 2019.	Previous reviews have addressed literature published before that time-frame, therefore, and since the topic under consideration is a rather fast developing field of research, earlier publications were not deemed relevant.
Articles that explicitly focus both on -Additive manufacturing AND -supply chain management OR -the SCOR dimensions.	This article tries to reveal the impacts of AM on SCs and hence research addressing this issue was included.
Articles that were written in English.	Only articles written in English were considered due to coding and research reasons.

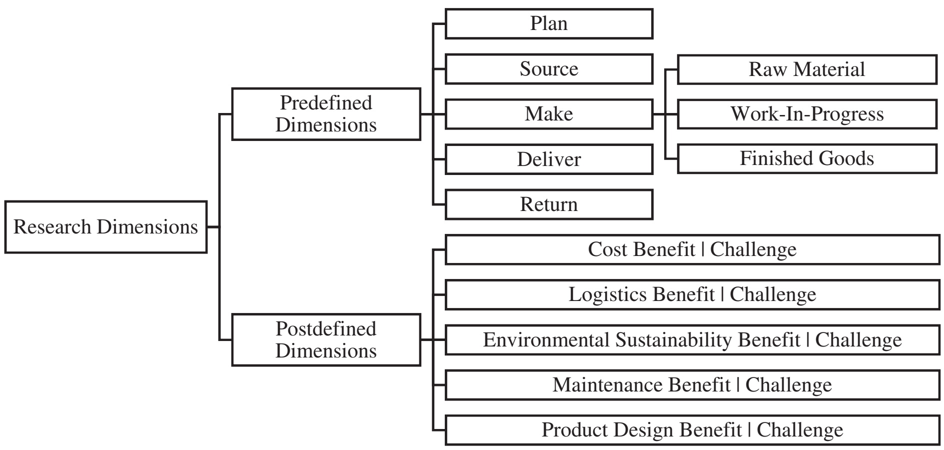

Figure 2. Simplified structure of the research dimensions for the qualitative analysis.

for Business Research (2018), or the 'SCIE' ranking by Clarivate Analytics (2018). Subsequently, two researchers independently applied a selection process to the 906 remaining articles to reduce bias and ensure consistency as recommended by Seuring et al. (2005). After a coordination meeting of two researchers that allowed in-depth discussion and debate as suggested by Petticrew and Roberts (2006) as well as Tranfield, Denyer, and Smart (2003), the researchers independently assigned all articles to one of three categories (Include, Maybe, Exclude) by reading the article titles and abstracts. For the sake of transparency, the performance of this selection process was evaluated (Spearman's Rho $= 0.8$ at $p < .001$). All articles marked as 'Include' by both researchers were directly included, articles evaluated with 'Include' and 'Maybe', 'Include' and 'Exclude', or 'Maybe' and 'Maybe' were then subjected to a full-text analysis, upon which an inclusion decision was made. Four articles were deemed relevant during this initial assessment process but were later discarded during the coding process due to a lack of actual relevance. This resulted in a final list of 141 relevant articles.

Definition of research dimensions

Decisions about categorising and analysing the literature should be based on the review questions and what has been planned in the protocol (Centre for Reviews and Dissemination 2009). Accordingly, all three authors identified the research dimensions in a two-step process following the example of Kunz and Reiner (2012) and Wankmüller and Reiner (2019). First, the so-called predefined dimensions were formulated. For this purpose, the SCOR framework (APICS 2017) was found suitable as it is widely applied in both academia as well as practice and it has previously been used to structure systematic reviews (Kamble, Gunasekaran, and Gawankar 2020; Chehbi-Gamoura et al. 2020). It includes five dimensions depicting the SC, namely 'Plan', 'Source', 'Make', 'Deliver', 'Return'. As it turned out that a substantial amount of the research focuses on the 'Make' dimension; this dimension was further split into subcategories. Hence, it was divided into a 'Raw Material', 'Work-in-progress' and 'Finished Goods' dimension (Simchi-Levi, Kaminsky, and Simchi-Levi 2008). Subsequently, the authors identified five postdefined dimensions by applying auto pattern finding, word frequency analysis, and word-tree diagram tools on the relevant articles. This was performed in NVivo, the software package used during this study. Auto pattern finding, a process through which the main concepts in the literature are identified automatically, was used to obtain an initial idea about the body of the literature. Then, a list of the 100 most frequent stemmed words was generated by applying a word frequency query. With the help of word tree diagrams – graphical representations of the connections between words in a text – their connections were analysed based on the aforementioned query. The most important topics were then grouped into five main dimensions under further

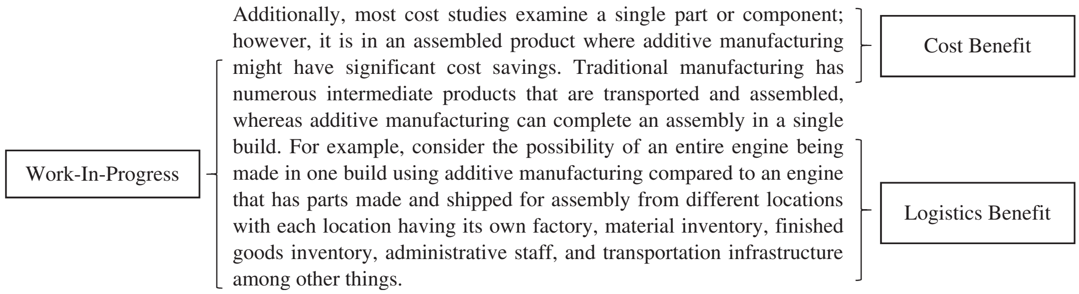

Figure 3. Worked example of content-based coding of a text paragraph from Thomas (2016) resulting in three new codes.

consideration whether the use of AM will be beneficial or challenging for these topics in an SC context (see Figure 2). For a more detailed explanation of the coding dimensions, refer to Appendix A. During the subsequent coding process, the overall number and the nature of the dimensions remained unchanged.

Analysis

There is a consensus in the literature about systematic literature reviews that to minimise human error and bias and to increase transparency, data should be extracted by a minimum of two reviewers (Rutter et al. 2006; Centre for Reviews and Dissemination 2009; Seuring et al. 2005). This data extraction was done by reading the articles and assigning text segments (i.e. full sentences) to the identified research dimensions. Once a text segment is assigned to a dimension, a so-called 'code' is created. If one text segment, for example, is assigned to two different dimensions, two codes are created, one for each dimensional assignment. In the worked example of the content-based coding process, as shown in Figure 3, three codes are created (while the overall number of dimensions remains unchanged). Once finished, the coding patterns were analysed to reveal profound insights into the literature at hand. Following the recommendation of both Hochrein et al. (2015) and Denyer and Tranfield (2009), the review structure and coding performance was repeatedly tested for their transparency and explanatory nature. Following the example of Seuring and Gold (2012) as well as Sauer and Seuring (2017), intercoder reliability was improved in an iterative process. Therefore, three coding runs were conducted in this systematic literature review before a sample of 21 articles were independently coded by two researchers and intercoder reliability was assessed on more than 800 codes. The Cohen's Kappa is the measurement metric of choice for this purpose (Seuring and Gold 2012) and during this study a Cohen's Kappa of 0.8057 was reached. Such a result indicates very high intercoder reliability according to Landis and Koch (1977), and upon reaching this result, the coding of the remaining articles was completed by one author. A total of 5933 content-based codes were assigned throughout the coding process, which allowed complex queries during the evaluation and analysis stage. Furthermore, all articles were also assigned to a research methodology, and an industry sector where applicable, to enable more advanced analysis. Based on the

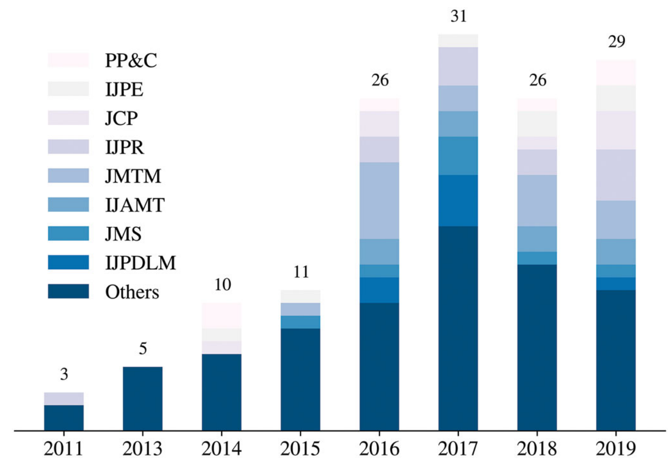

Figure 4. Articles per journal per year.

queries of these codes, two authors independently performed the final qualitative analysis and combined their results in discussion sessions to produce both the SCOR and industry-specific analysis.

Further research, discussion, and conclusion

Based on the results of the analysis, conclusions were drawn and further possible research areas regarding AM and its possible impacts on SCs were outlined.

Descriptive analysis

As elaborated in the previous section, the in-depth analysis of the systematic literature review is based on 141 articles. In this section, the aim is to present a descriptive analysis of both the article population as well as the quantitative results of the coding process. In more detail, this means that during the descriptive analysis information concerning the analysed literature as well as the distribution of the assigned codes will be presented in an aggregate and numeric form to give readers an idea about the underlying structure and patterns of both the material and the content.

As becomes evident from Figure 4, the number of relevant articles has grown significantly in the recent past which indicates the increased relevance of the application of AM in SCs. Furthermore, this development supports the aim of this article to provide a contemporary overview about key arguments observed in the scientific discourse. As the literature search was concluded in October 2019, not all articles

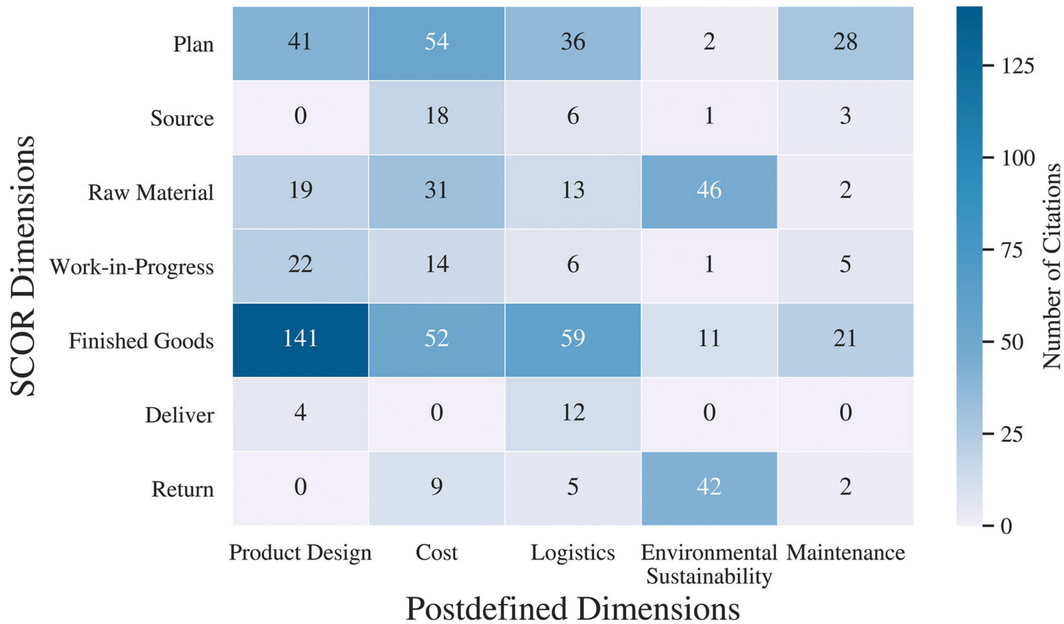

Figure 5. Number of codes per supply chain dimension.

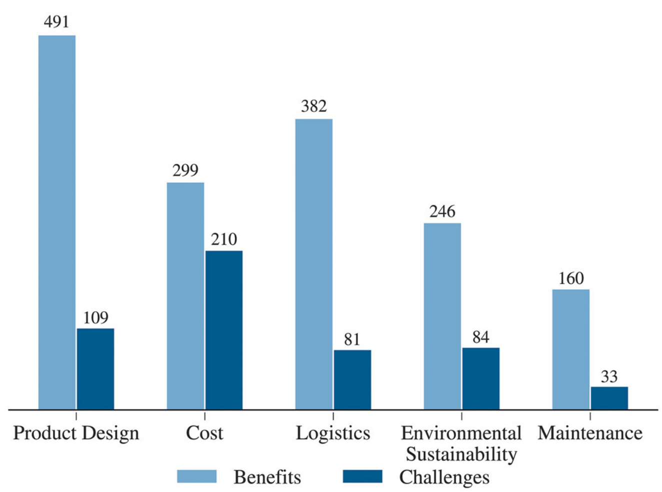

Figure 6. Benefits vs. challenges as identified through content-based analysis.

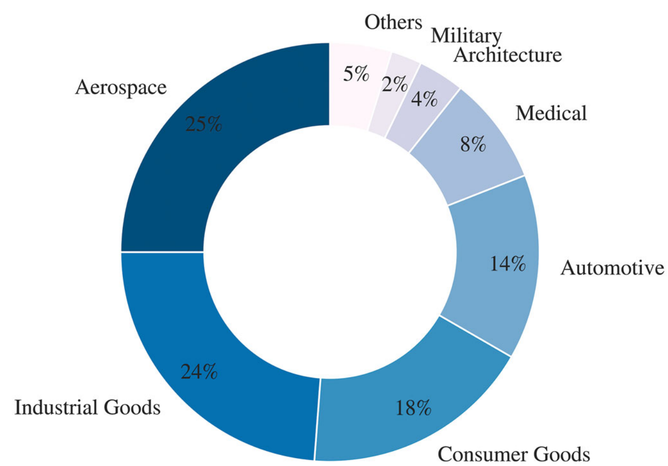

Figure 7. Number of articles per industry.

published in year 2019 were included. The academic journals most active in this context between 2008 and October 2019 are the 'Journal of Manufacturing Technology Management' (16 articles), the 'International Journal of Production Research' (12), and the 'International Journal of Advanced Manufacturing Technology' (8). The 'Journal of Manufacturing Systems' (7), 'International Journal of Production Economics' (7), 'Journal of Cleaner Production' (7), and the 'International Journal of Physical Distribution & Logistics Management' (7) all featured 7 relevant publications each, followed by 'Production Planning & Control' (6) with 6.

Figure 5 shows the number of codes per SCOR dimension that overlap with a corresponding code of a postdefined dimensions. Most of the research focuses on the 'Make' dimension of the SCOR framework, while the other dimensions receive less attention.

In Figure 6, the total number of codes in relation to the impact of AM on SCs for every postdefined dimension is shown. During the coding process, a distinction was made whether this impact can be regarded as beneficial or challenging. More specifically, this means that concerning the 'Cost' dimension, the literature explained beneficial impacts of AM on costs 299 times, while challenges were mentioned 210 times. Overall, it can be observed that benefits are more frequently mentioned in the literature than challenges, a circumstance that is discussed in more detail in the discussion and future research areas sections of this article. Furthermore, in the product design dimension for example, the disparity between the mentioned benefits and challenges is significantly higher than in the cost dimension. The particular benefits and challenges are explained in more detail in the qualitative analysis section.

The key industries are, as shown in Figure 7, aerospace and industrial goods followed by consumer goods and the automotive sector. This is in accordance with results achieved by Wohlers (2019) who found a similar distribution concerning the share of AM revenue created by different industrial sectors.

All articles were further categorised under at least one research methodology (in some cases, two research methodologies were applied). It was found that the used research methodology was uniform across the selected articles (Models [50], Case Studies [38], Conceptual [30], Survey Studies [22], and Reviews & Editorials [14]).

The identification of the postdefined dimensions as well as the descriptive analysis respond to *RQ1* whereas the following sections address the other two research questions.

Qualitative analysis

This section follows a clear structure and it is based on a qualitative analysis of the results of the coding process as described in previous sections. First, the coded arguments found in the literature are categorised according to the different SCOR dimensions through a software query in NVivo that allows for the creation of structured readouts of the manually coded content. These readouts were then independently interpreted by two researchers to further reduce bias (see review design section) with the aim to provide a thorough analysis of key themes as well as identified benefits and challenges in the relevant scientific literature. Second, industry specific arguments are reviewed and categorised. Each segment is independent, thus a reader interested in a certain domain might concentrate on the relevant segments only. To simplify the identification of the relevant categories, Table 3 provides a non-hierarchical summary of the most prominent arguments found in the existing literature for each SCOR dimension. Furthermore, the applied SCOR dimension interpretation is summarised at the beginning of each segment.

Plan

The 'Plan' dimension includes the assessment of supply resources, the aggregation and prioritisation of demand requirements, as well as the production, inventory, material, and capacity requirements planning (Bolstorff and Rosenbaum 2012).

Costs

Laplume, Anzalone, and Pearce (2016) explain that AM enables a distributed manufacturing approach which likely causes a reduction of transportation and packaging costs as compared to conventional SCs. Such distributed supply networks become feasible since low AM setup costs support a demand-driven reallocation of print jobs to the most suitable facility (Sasson and Johnson 2016), without high setup cost and long changeover times (Weller, Kleer, and Piller 2015). On the other hand, Chan et al. (2018) argue that distributed manufacturing will increase licencing and billing cost. Moreover, testing and extensive quality control might present an additional burden (Westerweel, Basten, and van Houtum 2018).

It was often argued that lacking economies of scale reduce the potential of AM for high production volumes (Weller, Kleer, and Piller 2015; Zhang, Zhang, and Han 2017). However, possible printing speed improvements and decreasing AM investment costs could make AM more viable for higher volumes in the future (Wagner and Walton 2016). Furthermore, optimisation algorithms have the potential to reduce the unit cost. For example, Li, Kucukkoc, and Zhang (2017) explain how allocating different parts in one printing job can significantly reduce AM unit cost as the AM build chamber will be utilised more efficiently.

Ghadge et al. (2018) discuss how short AM lead times reduce inventory cost throughout the product lifecycle while still achieving high service levels. Furthermore, the entire product development process profits from shorter cycle times and lower setup cost (Waller and Fawcett 2014). Moreover, costs become more controllable because the number of production steps and involved parties decrease (Thomas 2016). For example, Ben-Ner and Siemsen (2017) describe how AM supports the integration of several parts into one (also referred to as consolidation) which decreases the number of assembly steps and associated costs.

Generally, AM costs are still high and it is unclear how they will develop (Cohen 2014). Currently, investment in AM production capacity and knowledge is expensive and risky for most organisations (Thomas 2016; Weller, Kleer, and Piller 2015). This particularly holds because of fast technological advancements and rapidly changing market dynamics (Garmulewicz et al. 2018; Martinsuo and Luomaranta 2018). Pooling AM capacity across organisations might lessen associated cost and risk but increase the organisational effort (Togwe, Eveleigh, and Tanju 2019). Also, design improvements such as a lower product weight or higher functionality might reduce cost during the use phase of the product (Zanoni et al. 2019). Tosello et al. (2019) exemplified this potential by means of a production case used for injection moulding.

Environmental sustainability

Equipment selection and its adequate utilisation is often essential to reduce the ecological footprint (Faludi et al. 2015; Kellens et al. 2017). For example, both energy and resource consumption is often relatively high in case of low equipment utilisation (Chiu and Lin 2016).

Logistics

Distributed general purpose AM facilities allow the concentration of the production of various low-volume, high customisation, high urgency parts (Ratnayake 2019; Sasson and Johnson 2016) even in remote locations (Verboeket and Krikke 2019). This can increase SC throughput (Smith and Kerbache 2017). However, the increased flexibility and demand variability of distributed AM networks causes additional complexity for SC planning (Chowdhury et al. 2019). Process integration and SC simplification can however reduce administrative efforts such as material requirements planning (Do 2017). Furthermore, a dynamic adjustment of production volumes becomes possible as the production quantity can

Table 3. Typical arguments for each SCOR category.

SCOR expanded	Benefits	References	Challenges	References
Plan	Process integration and SC simplification reduce planning and management efforts.	Do (2017), Eyers and Potter (2015), Thomas (2016)	Lacking economies of scale and increase of stock keeping units due to customisation.	Weller, Kleer, and Piller (2015), Zhang, Zhang, and Han (2017)
	Capability to meet customer demands is enhanced through customisation and customer co-creation.	Jia et al. (2016), Oettmeier and Hofmann (2016)	Novel collaboration tools are needed to enable integration of new design and manufacturing capabilities.	Do (2017), Jia et al. (2016), Qian et al. (2019)
	Lead time is reduced because of AM across different phases of the product lifecycle.	Ghadge et al. (2018), Öberg and Shams (2019)	Skills development for new design possibilities is required.	Oettmeier and Hofmann (2016), Rylands et al. (2016), Shukla, Todorov, and Kapletia (2018)
Source	Instead of transporting finished goods or subcomponents, raw materials are sourced and transported that require less space and can be used in a wider production portfolio.	Ben-Ner and Siemsen (2017), Chen (2017)	AM machine producers can potentially restrict the supply of AM raw materials concerning type and purchasing channel.	Dawes, Bowerman, and Trepleton (2015), Mellor, Hao, and Zhang (2014)
Make – raw material	AM, as compared to subtractive manufacturing, uses less raw material to produce a given product due to its additive character.	Achillas et al. (2015), Chiu and Lin (2016), Kunovjanek and Reiner (2020)	AM raw materials are typically more expensive than materials used in conventional manufacturing.	Dawes, Bowerman, and Trepleton (2015), Scott and Harrison (2015), Waller and Fawcett (2014)
	More efficient raw material usage can reduce associated transportation efforts and related logistics activities.	Chen (2017), Gebler, Schoot Uiterkamp, and Visser (2014), Kothman and Faber (2016)	Limited range of raw materials available for AM.	Durach, Kurpjuweit, and Wagner (2017), Shukla, Todorov, and Kapletia (2018)
Make – work-in-progress	Due to the manufacturing freedom of AM, the consolidation of separate parts into one more complex part becomes possible which eliminates certain assembly needs.	Mothes (2015), Rylands et al. (2016), Strange and Zucchella (2017), Wagner and Walton (2016)	Consolidated parts have higher value and hence can eventually incur higher costs during maintenance or replacement.	Knofius, van der Heijden, and Zijm (2019a)
Make – finished goods	Customisation of products becomes feasible even in mass markets through the application of AM.	Attaran (2017), Bogers, Hadar, and Bilberg (2016), Weller, Kleer, and Piller (2015)	Economies of scale in the production process are lost or mitigated when switching to AM.	Baumers et al. (2013), Khajavi, Holmström, and Partanen (2018), Khajavi et al. (2015), Tosello et al. (2019)
	Tool-less production of finished goods shortens development cycles and lead-time.	Cohen (2014), Khajavi, Partanen, and Holmström (2014), Mothes (2015)	Costly and time-consuming finishing tasks might be required.	Livesu et al. (2017), Simons (2018)
Deliver	The localisation of production – closer to the consumer – can have a positive impact on delivery time and distance.	Attaran (2017), Muir and Haddud (2017), Steenhuis and Pretorius (2015), Kleer and Piller (2019)	Localised AM requires shifts of transportation patterns for the delivery of goods.	Chen (2017), Verboeket and Krikke (2019)
Return	AM allows the recycling of both AM waste material and of other non-AM wastes to be reused in the printing process.	Baechler, DeVuono, and Pearce (2013), Despeisse et al. (2017), Garmulewicz et al. (2018)	Technological challenges exist in the recycling process of wastes due to high-quality standards of AM raw material.	Nascimento et al. (2019), Peeters, Kiratli, and Semeijn (2019)

be matched with the number of products demanded (Rogers, Baricz, and Pawar 2016).

Maintenance

With AM, spare parts can be produced on demand and on location, which is especially beneficial when penalty costs are high (Li et al. 2019). It might simplify demand forecasting and planning while increasing system availability (Muir and Haddud 2017) and SC efficiency (Khajavi, Holmström, and Partanen 2018). Hence, downtime and inventory risks are likely to be reduced (Ghadge et al. 2018). This might even be enhanced through the repair of spare parts with AM (Portolés et al. 2016).

Furthermore, a virtual spare parts inventory management can reduce stock-out risks, inventory obsolescence (Sirichakwal and Conner 2016), and lead times (Öberg and Shams 2019). In this regard, Chekurov et al. (2018) revealed that there is a strong desire from practitioners to be able to order their spare parts centrally. Such a centralised spare parts system (or digital warehouse) can, according to Ballardini, Flores Ituarte, and Pei (2018), facilitate the processes of finding product information, pricing, and purchasing and, hence, can increase the company's process awareness given that a proper legal framework is in place.

Product design

Online co-creation of products directly between customer and manufacturer enables a close cooperation in the design process (Jia et al. 2016) and customer-specific inputs can be accounted for easily (Oettmeier and Hofmann 2016). This eliminates intermediate steps in the value chain (Eyers and Potter 2015; Kothman and Faber 2016). However, the result is a rapidly increasing number of unique designs and associated legal challenges (Bogers, Hadar, and Bilberg 2016; Weller, Kleer, and Piller 2015). For example, Chan et al. (2018) pointed out that customised designs might cause brand dilution or unexpected intellectual property violations.

A possible solution can be software and multi-platform integration. Especially, the exchange of design and manufacturing data to support product design, process planning, production planning, and execution of manufacturing operations is essential (Do 2017). This might be facilitated by a direct integration of E-commerce platforms when dealing with customised designs (Jia et al. 2016). Technologically, this could either be achieved with block-chain technology to trace the product history (Mandolla et al. 2019) or with cloud-based solutions that allow simultaneous access to product and process information (Qian et al. 2019).

Furthermore, AM offers the flexibility to optimise the design according to certain production constraints. For instance, the design can be selected according to the effort of certain assembly steps (Zhang, Zhang, and Han 2017). Moreover, it might become possible to modify and optimise designs iteratively (Fontana, Klahn, and Meboldt 2019). In any case, to harness most benefits, new skills, training, infrastructure, and work structures are required (Oettmeier and Hofmann 2016; Rylands et al. 2016). These efforts can either be realised internally or outsourced to specialised service providers (Shukla, Todorov, and Kapletia 2018).

Source

The 'Source' dimension deals with obtaining, receiving, inspecting, testing and purchasing of raw materials or finished goods (Bolstorff and Rosenbaum 2012).

Costs

A widespread use of AM and new AM raw material production methods will reduce sourcing costs. Simultaneously, this development will increase the number of available materials (Dawes, Bowerman, and Trepleton 2015). However, advanced material generation equipment is required that relies on high-quality raw material (Niaki and Nonino 2017). Additionally, AM machine producers might control the metal powders that can be processed on their respective machines, which can reduce the available material range, thus reducing competition and keeping costs high (Mellor, Hao, and Zhang 2014). Third party AM raw materials suppliers might represent an inexpensive alternative, but testing and the eventual adjustment of printing parameters remain a challenge (Simons 2018; Zanoni et al. 2019). Additionally, the high costs of quality AM machines is also a challenge (Scott and Harrison 2015; Woodson, Alcantara, and do Nascimento 2019).

Logistics

Since AM technology allows decentralised manufacturing, the transportation of finished goods and subcomponents is reduced. Most transportation movements shift upstream in the SC and are handled in the form of raw materials (Ben-Ner and Siemsen 2017). On the other hand, AM service providers face additional complexity when making procurement decisions. For example, AM raw materials could be procured from AM equipment suppliers, third party suppliers, or directly from powder atomisers, each of which has different benefits and challenges (Dawes, Bowerman, and Trepleton 2015).

Maintenance

Chekurov et al. (2018) argue that AM can change sourcing patterns for spare parts as AM technology reduces market entrance barriers. Moreover, Knofius, van der Heijden, and Zijm (2019b) show that setting up an alternative AM sourcing channel as soon as possible is often the best sourcing strategy for the maintenance of expensive capital goods. In particular, this holds if backorder and unit costs are high.

Make

The 'Make' dimension generally focuses on requesting and receiving material as well as manufacturing, testing, packaging, holding, and releasing of products (Bolstorff and Rosenbaum 2012).

Since the 'Make' dimension of the SCOR framework attracts most attention in the analysed literature (see Figure 5), it was further divided into 'Raw Material', 'Work-in-Progress', and 'Finished Goods'.

Make – raw material

Costs

A major cost benefit that can be gained by making products with AM is its high raw material efficiency that can decrease overall raw material costs (Achillas et al. 2015; Chiu and Lin 2016; Gebler, Schoot Uiterkamp, and Visser 2014). For metal AM, however, raw material costs are still a significant driver of the total manufacturing costs as they are typically more expensive than in conventional manufacturing (Waller and Fawcett 2014). In some cases, it can even be the largest cost factor (Dawes, Bowerman, and Trepleton 2015; Scott and Harrison 2015). Nevertheless, a further cost benefit can arise because AM shifts the customer-order decoupling point upstream in the SC; hence, most inventory will be kept in the form of raw material. This enables economies of scale and reduces inventory costs as the raw material can be shared between different products (Tsai 2017; Thomas 2016).

Environmental sustainability

The previously mentioned increased raw material efficiency of AM also effects the environmental sustainability positively (Attaran 2017; Bambach et al. 2017; Ben-Ner and Siemsen 2017; Chiu and Lin 2016; Faludi et al. 2015; Ford and Despeisse 2016). Not only is less raw material required but it can also be transported in powder form which allows a more efficient space utilisation and yields a reduction of carbon emissions (Li et al. 2017). Some benefits can also be carried over to the use phase of the products as light-weight products can reduce the environmental impact throughout the entire product lifecycle (Böckin and Tillman 2019). Unfortunately, some of these sustainability benefits are offset by high carbon emissions during raw material production (Li et al. 2017). Moreover, a high process energy requirement compared to traditional manufacturing increases the ecological footprint (Ingarao et al. 2018).

Logistics

The reduced raw material consumption during the manufacturing process reduces transportation efforts and related logistics activities (Chen 2017; Gebler, Schoot Uiterkamp, and Visser 2014; Kothman and Faber 2016). This potential can be further enhanced through local and flexible material markets that might benefit from localised recycling activities (Despeisse et al. 2017; Garmulewicz et al. 2018) and reduced SC risks (Strange and Zucchella 2017). A downside is that some AM processes need high-quality resources that are sometimes difficult to transport due to their physical or chemical properties (Meisel et al. 2016).

Maintenance

A possible maintenance benefit to be gained in this context is that AM might enable more resource efficient repairs of industrial goods (Ford and Despeisse 2016). However, at this point, the potential is limited due to compatibility issues between conventional and additive material properties (Ratnayake 2019).

Product design

The material science community has significantly improved the range of raw materials available for AM (Deschamps et al. 2017; Petrovic et al. 2011) and new combinations of raw materials become available (Evans 2013). This and the design freedom of AM enables product optimisation, which can also increase raw material efficiency (Deschamps et al. 2017; Evans 2013; Ford and Despeisse 2016; Ingarao et al. 2018; Strange and Zucchella 2017; Kunovjanek and Reiner 2020). However, additional raw materials have to be developed in order to exploit the design freedom of AM to its full potential (Durach, Kurpjuweit, and Wagner 2017; Shukla, Todorov, and Kapletia 2018).

Make – work-in-progress

Product design

Due to the design freedom of AM, the consolidation of separate parts into one more complex part becomes possible (Weller, Kleer, and Piller 2015; Waller and Fawcett 2014; Wagner and Walton 2016; Strange and Zucchella 2017; Rylands et al. 2016; Mothes 2015; Kellens et al. 2017; Ben-Ner and Siemsen 2017; Grzesiak, Becker, and Verl 2011; Knofius, van der Heijden, and Zijm 2019a). Overall, products could even be of higher quality with novel designs that were previously not feasible (Bambach et al. 2017; Kellens et al. 2017).

Costs and maintenance

Consolidation leads to a reduction of assembly steps which in turn reduces intermediate part costs such as handling, inventory, and labour costs (Achillas et al. 2015; Mothes 2015; Weller, Kleer, and Piller 2015). Also involved are diminishing costs for bolts, screws, welding, and the like (Thomas 2016). In the spare parts domain, parts consolidation can remove potential failure modes and increase reliability compared to the regular component which has a large effect on the total lifecycle costs (Westerweel, Basten, and van Houtum 2018). However, since parts become more complex and specific, the total costs (including logistics, manufacturing and repair costs) might also increase; particularly, maintenance operations often become more expensive as now the entire high-value part has to be replaced as compared to potentially cheaper assembly parts. Hence, it is important to consider the total costs in case consolidation is included (Knofius, van der Heijden, and Zijm 2019a).

Logistics and environmental sustainability

Consolidation further decreases material flows and simplifies value chains by making them less hierarchical with fewer production steps (Laplume, Petersen, and Pearce 2016; Kleer and Piller 2019), fewer suppliers (Öberg and Shams 2019), and reduced environmental impacts (Ford and Despeisse 2016).

Make – finished goods

Costs

The direct digital manufacturing capabilities of AM can reduce SC complexity, lead time, freight volume, and corresponding costs (Bogers, Hadar, and Bilberg 2016; Chen 2016; Durach, Kurpjuweit, and Wagner 2017). Companies already consider the trade-off between printing products close to the customer compared to long-distance shipments. Therefore, more and more AM production capacity is created around the world which ultimately might even reduce market entry barriers (Rehnberg and Ponte 2018). Especially, printing low-volume goods such as tooling or spare parts reduce investment costs and lead times (Achillas et al. 2015; Cohen 2014; Tosello et al. 2019). Furthermore, AM can be beneficial for launching new products as it significantly reduces up-front investments (Khajavi et al. 2015; Weller, Kleer, and Piller 2015). Furthermore, low-cost mass-customisation can become feasible (Attaran 2017; Bogers, Hadar, and Bilberg 2016; Weller, Kleer, and Piller 2015). Such capabilities are also relevant for the production of spare parts for which AM might present itself as a cost-efficient solution to improve system availability at remote locations (de La Torre, Espinosa, and Domínguez 2016).

Even though AM production or certification costs for spare parts are often much higher than with conventional manufacturing, they can still be acceptable as associated inventory and transportation costs decrease significantly (Sasson and Johnson 2016; Knofius, van der Heijden, and Zijm 2016). Economies of scale, however, are lost in the production process and thus render AM less viable for higher volumes as the per-piece price is relatively high (Baumers et al. 2013; Khajavi et al. 2015; Khajavi et al. 2018; Tosello et al. 2019). The primary reasons for this are high AM equipment and material costs as well as low utilisation rates and slow machine throughput times that hinder a broader application of AM (Ben-Ner and Siemsen 2017; Huang et al. 2017; Scott and Harrison 2015). To that end, the efficient utilisation of the build chamber capacity is also important (Baumers et al. 2013) which provides one reason why the production of larger parts is usually relatively more expensive (Wagner and Walton 2016). Finally, cleaning parts from excess powder, support structure removal, and other finishing tasks still have to be performed manually which increases the AM production cost as well (Simons 2018).

Environmental sustainability

Design improvements such as weight reduction, part consolidation, improved airflow, and thermal efficiency often enhance environmental sustainability during the use-phase of final parts (Ford and Despeisse 2016; Gebler, Schoot Uiterkamp, and Visser 2014; Faludi et al. 2015; Böckin and Tillman 2019). Yet, inexperienced users often decrease the efficiency of the AM process and hence cause more CO2 emissions (Cerdas et al. 2017). Moreover, for metal printing, the high requirement of process energy reduces the eco-balance of AM (Ingarao et al. 2018). On the positive side, the measurement of process energy consumption and carbon accounting becomes more transparent compared to conventional manufacturing methods as the production process is simplified (Baumers et al. 2013).

Logistics

A widely recurring argument is that printing parts on demand and close to the customer reduces SC complexity, transportation, and logistics (Birtchnell and Urry 2013; Durach, Kurpjuweit, and Wagner 2017; Rogers, Baricz, and Pawar 2016; Bogers, Hadar, and Bilberg 2016; Chen 2016, 2017; Gress and Kalafsky 2015; Kothman and Faber 2016; Scott and Harrison 2015; Smith and Kerbache 2017; Laplume, Anzalone, and Pearce 2016; Halassi, Semeijn, and Kiratli 2019). The production might be executed at regional super-centres which bundles the production of various low-volume parts. Not only does this hold benefits in terms of economies of scope for raw materials but it also allows better equipment utilisation and the sharing of high investment costs (Sasson and Johnson 2016). As finished goods can be directly produced from 3 D model data, holding inventory becomes less important (Ben-Ner and Siemsen 2017; Sasson and Johnson 2016; Scott and Harrison 2015; Verhoef et al. 2018) and lead times become shorter (Attaran 2017; Ben-Ner and Siemsen 2017; Bogers, Hadar, and Bilberg 2016; Dwivedi, Srivastava, and Srivastava 2017; Khajavi et al. 2015; Knofius, van der Heijden, and Zijm 2016; Liu et al. 2014). Nevertheless, in the AM supply chain, significant time is spent on the production process (Huang et al. 2017) which is also the key reason why AM cannot match the efficiency of mass production for larger production quantities (Fawcett and Waller 2014).

Maintenance

Maintenance benefits through direct manufacturing of finished goods predominantly arise in the context of spare parts production. Printing spare parts on demand and on location reduces inventories and lead times which in turn might increase system availability (Eyers and Potter 2015; Ghadge et al. 2018; Liu et al. 2014; Verhoef et al. 2018; Wagner and Walton 2016; Sirichakwal and Conner 2016; Sasson and Johnson 2016; Waller and Fawcett 2014). Since tooling is not required, spare parts can be easily produced at different locations (Khajavi, Partanen, and Holmström 2014) and consumers can print their spare parts themselves to repair previously purchased products. This allows faster, more specific solutions and extended product lifecycles (Attaran 2017; Eyers and Potter 2015). AM allows the production of a variety of spare parts with the same equipment and material which makes it particularly interesting for production at remote locations (Attaran 2017; Eyers and Potter 2015; Meisel et al. 2016; de La Torre, Espinosa, and Domínguez 2016). Moreover, these capabilities have huge potential in the case of legacy systems in which parts are no longer produced or available on the market (Ballardini, Flores Ituarte, and Pei 2018).

Product design

Various articles mention that geometric complexity is no longer an obstacle in the AM process which allows new design approaches (Cohen 2014; Ford and Despeisse 2016; Gress and Kalafsky 2015; Grzesiak, Becker, and Verl 2011; Mothes 2015; Niaki and Nonino 2017; Neugebauer et al. 2011; Rehnberg and Ponte 2018; Simons 2018; Sirichakwal and Conner 2016; Steenhuis and Pretorius 2015; Chan et al. 2018; Chowdhury et al. 2019; Colosimo et al. 2018). This includes complex internal structures (Deschamps et al. 2017; Neugebauer et al. 2011; Petrovic et al. 2011; Zeltmann et al. 2016; Zanoni et al. 2019). Particularly, because complex designs can be manufactured without dedicated tools or moulds (Ben-Ner and Siemsen 2017; Cohen 2014; Khajavi, Partanen, and Holmström 2014; Mothes 2015; Neugebauer et al. 2011; Niaki and Nonino 2017; Simons 2018; Weller, Kleer, and Piller 2015; Fontana, Klahn, and Meboldt 2019).

Therefore, AM often allows an increase in the functionality of final parts (Elverum and Welo 2016; Ford and Despeisse 2016; Grzesiak, Becker, and Verl 2011; Kellens et al. 2017; Kothman and Faber 2016; Rylands et al. 2016; Thomas 2016). Additionally, certain creative activities can be shifted from the manufacturer to the consumer/user (Bogers, Hadar, and Bilberg 2016; Rogers, Baricz, and Pawar 2016; Chen 2017; Eyers and Potter 2015; Jia et al. 2016; Kothman and Faber 2016). Not only does this hold benefits in terms of design improvements but also strengthens the relationship between customer and producer (Niaki and Nonino 2017; Waller and Fawcett 2014). Furthermore, in the fashion industry, the manufacturing flexibility of AM is well-suited for frequent trend changes (Cerdas et al. 2017).

Product design challenges were less frequently discussed in the literature in the context of finished goods. However, Durach, Kurpjuweit, and Wagner (2017) point out that full mass-customisation is still not a very likely scenario due to many challenges. For example, Ford and Despeisse (2016) as well as Verboeket and Krikke (2019) explain that specific (and expensive) design skills are required to exploit design freedom with AM. Moreover, size limitations of the build chamber often rule out the production with AM (Attaran 2017). Furthermore, support materials and their removal introduces additional constraints that are particularly restrictive for complex infills and cause additional effort to reach the required part quality (Livesu et al. 2017). Finally, part quality remains a big challenge if parts are operated in extreme environments such as under high pressure or high temperature (Fawcett and Waller 2014).

Deliver

The 'Deliver' dimension comprises picking, packing and the configuration of products, the consolidation of orders, and the outbound transportation processes with shipping, import, and export. It also includes managing accounts receivables and the customer database (Bolstorff and Rosenbaum 2012).

Logistics

AM can improve out-bound logistics by shortening the SC as well as delivery time and distance (Attaran 2017; Muir and Haddud 2017; Steenhuis and Pretorius 2015; Kleer and Piller 2019). This can result in an improvement of on-time delivery performance (Muir and Haddud 2017). It is especially important in cases in which the perceived timing of a need for the product and its arrival at the user's location is relatively short (Hannibal and Knight 2018). A further logistical benefit arises due to the localisation of production. Customers can approach a local retailer with their needs and a direct distribution to the customer is possible (Jia et al. 2016). Such a localisation means that traditional producer countries might suffer a demand reduction, hence, structural changes are necessary. For example, it is likely that container flows will change and that small trucks will be used more frequently (Chen 2017; Verboeket and Krikke 2019).

Maintenance

The shortened delivery time of AM products is of special interest for spare parts SCs. Through the utilisation of AM technology, spare parts can be manufactured closer to the point of need, which shortens delivery time and reduces downtime costs (Khajavi, Holmström, and Partanen 2018).

Return

The 'Return' dimension copes with defective, warranty, and excess return, disposition and replacement including scheduling and administration (Bolstorff and Rosenbaum 2012).

Environmental sustainability

For the 'Return' dimension, the most important aspect in the literature is that AM allows the recycling of both AM waste material and of other non-AM wastes. Recycling not only reduces the requirement for virgin materials but also increases sustainability and energy efficiency of the AM production process (Baechler, DeVuono, and Pearce 2013; Despeisse et al. 2017; Garmulewicz et al. 2018; van Le, Paris, and Mandil 2017; Mami et al. 2017; Meisel et al. 2016; Niaki and Nonino 2017; Strange and Zucchella 2017). Especially, if a distributed recycling concept is employed, emissions related to the collection and transportation of wastes can be reduced (Chen 2017; Baechler, DeVuono, and Pearce 2013; Garmulewicz et al. 2018; Kreiger et al. 2014). Reused materials for AM include plastics, metals, and even organic wastes such as wood, but the processing for recycling can be cumbersome (Nascimento et al. 2019). Moreover, for various products, consumers demand high (aesthetic) quality which could sometimes rule out the use of recycled materials (Peeters, Kiratli, and Semeijn 2019).

Maintenance

Tools and dies can be remanufactured with AM which increases the usage period (Schniederjans and Yalcin 2018). Similarly, AM can be used to repair end-of-life products (van Le, Paris, and Mandil 2017).

Industry sectors

Table 4 presents an overview of the addressed business cases per industry sector in the literature.

The qualitative assessment of the arguments observed in the literature concerning the different areas of the SC concludes the response to RQ2.

Discussion

The following section will start out by discussing the results of this study in relation to other literature-based studies focussing on AM and SCs. In the benchmark study, Niaki and Nonino (2017) reviewed the literature on the management of AM for which they predominantly relied on quantitative analysis tools. This study did also consider earlier publications

Table 4. Business cases per industry sector.

Industry	Business case	Authors
Industrial Goods	Production of spare parts and other goods with sporadic demand	Achillas et al. (2015), Chekurov et al. (2018), Durão et al. (2017), Muir and Haddud (2017)
	Product recycling, remanufacturing and repair with AM	Baechler, DeVuono, and Pearce (2013), Bambach et al. (2017), Ford and Despeisse (2016), van Le, Paris, and Mandil (2017)
	Localisation of production and its implications	Gebler, Schoot Uiterkamp, and Visser (2014), Huang et al. (2017), Durão et al. (2017)
	Raw material efficiency	Ingarao et al. (2018), Bambach et al. (2017)
	Combination with other manufacturing techniques to increase performance	Bambach et al. (2017), Mothes (2015), van Le, Paris, and Mandil (2017), Tosello et al. (2019), Zanoni et al. (2019)
	Product redesign and customisation	Petrovic et al. (2011), Rylands et al. (2016), Simons (2018), Westerweel, Basten, and van Houtum (2018), Ingarao et al. (2018)
Military	Distributed production of spare parts and other goods	Audette et al. (2017), Meisel et al. (2016)
Construction	Architectural designs and the production of scale models	Kothman and Faber (2016), Attaran (2017)
	Additively built structures with concrete	Verhoef et al. (2018), Kothman and Faber (2016), Attaran (2017)
Medical	Fabrication of personalised and optimised medical goods such as implants, prosthetics, or instruments	Ben-Ner and Siemsen (2017), Attaran (2017), Eyers and Potter (2015), Gebler, Schoot Uiterkamp, and Visser (2014), Ramola, Yadav, and Jain (2019)
	Additively manufactured body parts and human organs	Attaran (2017), Ramola, Yadav, and Jain (2019)
Aerospace	Printing spare parts on demand, on location	Attaran (2017), Eyers and Potter (2015), Ghadge et al. (2018), Khajavi, Partanen, and Holmström (2014), Khajavi, Holmström, and Partanen (2018), Knofius, van der Heijden, and Zijm (2016), Liu et al. (2014), Mandolla et al. (2019), Rehnberg and Ponte (2018), Togwe, Eveleigh, and Tanju (2019), Verhoef et al. (2018), Wagner and Walton (2016), Westerweel, Basten, and van Houtum (2018)
	Reduced weight, fuel requirement, and emissions	Attaran (2017), Deschamps et al. (2017), Gebler, Schoot Uiterkamp, and Visser (2014), Mami et al. (2017), Mellor, Hao, and Zhang (2014), Tang, Mak, and Zhao (2016), Togwe, Eveleigh, and Tanju (2019), Verhoef et al. (2018), Wagner and Walton (2016), Westerweel, Basten, and van Houtum (2018), Ford and Despeisse (2016)
	Unique designs	Attaran (2017), Mellor, Hao, and Zhang (2014), Rehnberg and Ponte (2018), Tang, Mak, and Zhao (2016), Wagner and Walton (2016)
	Less waste during production	Gebler, Schoot Uiterkamp, and Visser (2014), Khajavi et al. (2018), Mami et al. (2017), Mellor, Hao, and Zhang (2014), Rehnberg and Ponte (2018), Tang, Mak, and Zhao (2016), Verhoef et al. (2018), Wagner and Walton (2016), Ford and Despeisse (2016)
	Reduced tooling and assembly requirements	Khajavi et al. (2018), Rehnberg and Ponte (2018), Verhoef et al. (2018), Wagner and Walton (2016), Westerweel, Basten, and van Houtum (2018)
	Repair and qualification of parts	Portolés et al. (2016)
	Shorter product development cycles	Rehnberg and Ponte (2018)
	Economic production for low volume or obsolescence parts	Ghadge et al. (2018), Khajavi, Partanen, and Holmström (2014), Knofius, van der Heijden, and Zijm (2016), Rehnberg and Ponte (2018)
	Increased SC responsiveness	Khajavi et al. (2018)
Automotive	Reduction of assembly steps due to part integration	Thomas (2016), Ben-Ner and Siemsen (2017), Dwivedi, Srivastava, and Srivastava (2017)
	Customisation of vehicle designs and layouts	Ben-Ner and Siemsen (2017), Dwivedi, Srivastava, and Srivastava (2017)
	Printing spare parts on demand, on location	Böckin and Tillman (2019), de La Torre, Espinosa, and Domínguez (2016)
	Unique designs and design optimisation through rapid prototyping	Elverum and Welo (2016), Neugebauer et al. (2011), Dwivedi, Srivastava, and Srivastava (2017), Rehnberg and Ponte (2018), Zanoni et al. (2019)
	Reduced fuel consumption and environmental impact due to design optimisation and lower weight	Böckin and Tillman (2019)
	Increased customer orientation and supplier integration	Delic, Eyers, and Mikulic (2019)
Consumer Goods	Product customisation, personalisation, and redesign	Jia et al. (2016), Bogers, Hadar, and Bilberg (2016), Chiu and Lin (2016), Do (2017), Ben-Ner and Siemsen (2017), Attaran (2017), Rylands et al. (2016)
	Speed-up of development and time to market	Chiu and Lin (2016), Attaran (2017)
	Localised production and shorter delivery	Chen (2017), Jia et al. (2016), Cerdas et al. (2017), Bogers, Hadar, and Bilberg (2016), Kreiger et al. (2014), Laplume, Anzalone, and Pearce (2016), Ben-Ner and Siemsen (2017), Attaran (2017), Steenhuis and Pretorius (2015)
	Customer co-creation	Bogers, Hadar, and Bilberg (2016), Do (2017), Rylands et al. (2016)
	Recycling and reuse of consumer goods through AM	Kreiger et al. (2014)
	More efficient production planning and resource utilisation	Qian et al. (2019)

(years 1990-2014), therefore our study is not only methodologically different but also covers a different time-frame. Several potential SC relevant pathways were laid out, but they acknowledge that the overall research activity in regard to AM and SCs was just taking off when they conducted their study, hence supporting the findings of our study. A more recent review by Fosso-Wamba (2017) addressed AM supply chain issues while also acknowledging that this is performed with a very limited focus. While some findings are in line with this study, a major difference became evident concerning their conclusion that AM will mostly focus on reusing previously created designs. In our study, we show that various industries are highly interested in AM for the manufacturing of finished goods and even consider it as a potential standard manufacturing approach. This extends well beyond the simple reuse of designs into opening entirely novel design and manufacturing approaches. In a methodologically similar yet contextually different study, Ryan et al. (2017)

summarised the discussion about future AM supply chain scenarios. They identified engineer-to-order and make-to-order as the most likely SC scenarios with AM. While this generally corresponds to the perception gained throughout the current study a differentiation between industry-specific applications or between different SC areas is entirely missing. Both of these are key elements addressed in this review article; therefore, they can be regarded as complementary. Verboeket and Krikke (2019) presented a literature review with the conclusion that AM is mainly used for small, low demand and geometrically complex products. While this seems accurate for the current application, trends identified in this systematic review show that other scenarios are also possible. Furthermore, industry-specific implications are not analysed conclusively. Finally, the articles by Boon and van Wee (2018), Guo and Leu (2013), Jin et al. (2017), and Steenhuis and Pretorius (2015) either focus on technological aspects or provide unstructured reviews that are primarily meant to motivate future research directions. Considering these shortcomings, the current study clearly differentiates itself from previous work.

To continue, the descriptive analysis section revealed several trends and implications. First, the research interest about the impact of AM on SCs is increasing significantly over the last couple of years. Second, the 'Make' dimension of the SCOR framework received by far the most attention; but for industry it is also essential to address different topics such as how AM influences planning activities and how it can be integrated in existing business processes. Third, the benefits of AM were more frequently discussed than challenges which helps attract attention but leaves related obstacles unsolved.

In the qualitative analysis section, the main arguments were structured and analysed. The following discussion critically assesses these arguments with a focus on distinguishing between empirically proven and conceptually envisioned impacts of AM. The first SCOR dimension is 'Plan' and from a planning perspective, costs and process integration of AM are primary issues both of which are well studied empirically and conceptually. Purchasing AM equipment and training qualified professionals is certainly expensive but proper integration into the SC is a complex task as well. The proposed solution methods such as electronic cooperation tools, digital product platforms, and product repositories still have to be proven in a practical environment. Long-term planning decisions concerning AM adoption and integration remain challenging in the real world due to rapid technological advancements and a challenging legal framework. Overall, AM remains most suitable for the production of goods with a high product value, low or intermittent demand, individual designs, and short desired lead times.

Concerning the 'Source' dimension, there is consensus in the analysed literature that AM raw materials are quite expensive compared to raw materials for conventional manufacturing. In particular, depending on the raw material type, this can be caused by the strong position of AM equipment producers. Additionally, high-quality industrial AM machines are expensive which makes equipment sourcing a challenging task for smaller companies. These aspects are well supported empirically. The integration and impact of AM on sourcing tasks on the other hand is predominantly analysed conceptually, and studies explicitly focussing on the integration of AM in the current sourcing process are sparse.

The dominant topic in the 'Raw Material' dimension is the material efficiency of AM in the production process. Due to the layer-based production technique, AM uses less raw material when manufacturing a product, which has also been shown in multiple empirical analysis. Two major issues however prevail that might offset this benefit: the high cost of AM raw material and the limited range of materials that can be used for AM. Whether AM will reduce logistic efforts due to its material efficiency has so far only been analysed theoretically and is still to be manifested in practical applications. Similar issues exist concerning the storage and transportation requirements of AM material; maintaining material properties and quality can be challenging and limit some of the envisioned benefits.

Parts consolidation is the overarching topic when it comes to the 'Work-In-Progress' dimension. It has been shown in multiple applications that the greater design freedom of AM can indeed lead to a consolidation of separate parts into one more complex part. This has various implications for the SC that are not all well understood. From a theoretical perspective, it was even shown that consolidation can have a negative impact on costs and maintenance.

The production of 'Finished Goods' is the dimension which attracted most attention in the literature. There are well-documented arguments with empirical evidence, and case studies of various scopes have been conducted. The addressed benefits in this category mostly revolve around the design freedom of AM and the low setup costs. Some of the mentioned benefits are offset by quality concerns and the dependency on skilled labour.

For the 'Deliver' dimension, it was indicated that AM has the potential to shorten delivery time and distance due to localised manufacturing. Such a concept sounds appealing but practical applications of the bespoke SC approach are still sparse and hence it remains uncertain whether potential benefits outweigh challenges. For example, certification and product quality are major obstacles for the direct delivery of additively manufactured goods to the end customer.

In the 'Return' dimension, the usage of recycled material for AM was widely discussed. In this context, the recycling of AM material, especially used powders, is already common practice. It was demonstrated how extrusion-based methods can involve the use of recycled plastics. Recycling metals, on the other hand, is a difficult process about which little empirical evidence of successful cases exists. The direct remanufacturing of products is also a potential field of application for AM. However, challenges concerning quality and economic feasibility remain.

Future research areas

During the analysis of the coding results as well as the subsequent discussion, a disparity between investigated benefits

Table 5. Potential research questions and methodologies for future research.

SCOR dimension	Research question	Potential methodology
Plan	How does the supply chain location influence the investment decision in decentralised AM?	Model building (Cost modelling; Cost optimisation)
	Which in-house AM production option is most suitable for which company?	Case research Model building (empirical quantitative models; scenario analysis)
	Which company characteristics determine the value of in-house AM production?	Case research Survey research Systematic literature review
	How does documentation and data storage influence the ecological footprint of distributed AM?	Grounded theory Model building (lifecycle assessment) Experimental research
	How can intellectual property rights be shared and secured with AM in a distributed supply chain?	Game theory
Source	When should companies move to third-party raw material supply for AM?	Case research
	Which technologies can support the traceability of AM raw material supply?	Experimental research Survey research
	What AM sourcing concepts have successfully been applied in real-world supply chains?	Case research Systematic literature review
Make	How will the roles of traditional manufacturing companies and logistics providers shift in a distributed SC?	Model building (System dynamics; Agent-based modelling)
	How will AM know-how be distributed in the case of customer co-creation?	Case research
	How can challenges regarding the transport of high-tech AM raw material be tackled in real-life?	Experimental research Case research
	Which post-processing steps can be automized and how will this impact manufacturing cost?	Model building (Cost modelling)
Deliver	What are the impacts of a decentralised AM supply chain on last-mile delivery operations?	Model building (Discrete event simulation; State-space modelling)
	Which attributes hamper the establishment of distributed international AM supply chains?	Case research Survey research Systematic literature review
	What is the economic potential of custom circumvention?	Model building (Cost modelling)
Return	How to locate recycling infrastructure from an ecological and economical perspective?	Model building (Threshold analysis)
	What is the role of the end-consumer in a closed-loop AM supply chain?	Case research Survey research

and challenges of AM and its effects on the SC became evident. While the emphasis on benefits appears desirable during the exploration phase of a new application, it becomes increasingly important to address AM challenges to mitigate obstacles concerning technology adoption and implementation. The following section presents future research directions for each SCOR dimension, potential future research questions and envisioned methodological approaches (see Table 5) following the methodological guidance of Ahlstrom (2016).

Plan

Decentralisation tends to increase the throughput and efficiency of the SC yet it remains unclear when and how organisations, depending on the location in the SC, should invest in this opportunity.

Future research is required to analyse the type of organisations which should invest in AM production capacities. While the literature seems to emphasise in-house production capacities, the authors believe that various organisations will rather rely on external capacities or leasing concepts. Economic and ecological trade-offs demand further (quantitative) attention to develop guidelines. Intellectual property rights are also a major obstacle for the digitalisation of the SC and overcoming this problem requires a higher degree of cooperation between organisations across the SC. Accordingly, game theoretical SC analyses or the application of novel technologies, such as blockchain, have been mentioned as possible solutions.

Source

AM machine producers predominantly control raw material supply, but third-party raw material suppliers are gradually entering the market; further decision support is required in this context. First, the influx of different raw material supply sources demands higher traceability to support the certification process of the final product. Second, decision support on when to switch between original raw material and third-party material is required. Third, the existing scientific literature tends to generalise the role of equipment suppliers in regard to raw material supply, a point that should be analysed more discriminately. Further, some research has been conducted on how AM can be integrated in the product sourcing process through dual or hybrid sourcing strategies, a stream that requires more empirical evidence.

Make

With AM some consumers or service providers such as DHL or Amazon take over manufacturing responsibilities.

Therefore, it is essential to study new business models for manufactures or IP owners in general. Further, challenges of transporting high-tech AM raw material and support materials such as (explosive) gases for the build chamber have not received sufficient attention. Additionally, finishing tasks have traditionally been conducted manually, but with general technological advancement and current progress in the automatisation of post-processing this can change. Most current cost estimations are based on manual post-processing; hence an up-to-date cost estimation can be a potential future line of research, also analysing varying levels of automized post-processing.

Deliver

While localisation is a key topic in other SCOR dimensions as well as in certain industries, the effects on the delivery process have not been discussed sufficiently. A promising application might be to evaluate the possibility of passing customs or attaining compliance with varying international quality standards and certifications. Further, as Chekurov and Salmi (2017) have shown in their study, it matters where in the business network AM is performed. Placing AM machines closest to the point of need can be beneficial, the feasibility of which also requires further investigation.

Return

Future research is required to determine what is best from an economic and ecologic perspective concerning decentralised recycling for AM. Recycling facility locations and implementation should be analysed, regarding when the shift from centralised to distributed recycling should occur. The application of circular economy knowledge on AM and SCs might also be of interest, especially concerning the role of consumers in a closed-loop AM supply chain as they are the ones actually disposing or returning used AM goods.

Industries

In several industries, new research is in the pipeline concerning the AM application in SCs. In the military domain Montero et al. (2018) emphasised the potentials of AM for spare parts management and maintenance during field deployments. Additionally, Boer, Lambrechts, and Krikke (2020) analysed the related responsiveness, efficiency and most notably sustainability of the spare parts supply chain in the military domain. Here, more empirical research is required depicting application cases. Similarly, the production of critical spare parts also offers economic value in the aerospace industry, high certification costs, however, currently hamper further exploration of this application. Therefore, it seems promising to relate to the effect on spare parts management in other industries for which certification is a less critical issue. Another industry where more research is required is pharma. Zhang et al. (2018), as well as Akmal et al. (2018), have already taken the first strides into the investigation of personalised drug delivery systems. Besides medical investigation, operations and SC researchers need to contribute to this novel field of AM application. Major changes concerning the impacts of AM on SCs became evident during the Covid-19 pandemic. While lying outside of the scope of this article, it is an interesting future stream of research. Choong et al. (2020) elaborated on the responsiveness of AM as goods that were under shortage, such as personal protective equipment, were produced by AM with little delay. Salmi et al. (2020) stressed the importance of open source solutions in this context and Sinha, Bourgeois, and Sorger (2020) regarded the distributed and decentralised nature of the AM response. In this regard, empirical research mapping, analysing, and describing the shifting role of AM during the pandemic is most desired.

Study limitations

The main limitation of this study is the qualitative nature of the systematic literature review. Even, though the study was conducted according to the highest methodological standards, where all data extraction steps were performed by two authors independently to reduce bias while also measuring their performance, a degree of uncertainty remains concerning the critical assessment of study contents. Furthermore, not all articles that might be of interest were included despite a structured selection process. Retrieving articles from additional scientific databases – such as Google Scholar, Scopus, or Engineering Village – could potentially lead to the inclusion of further relevant articles. More importantly, however, relaxing the inclusion criteria and quality requirements could also expand the body of literature in regard to quantity. Moreover, industry reports and 'grey literature' – posted on internet forums, dedicated homepages, and chatrooms – are an important source of information especially in a fast developing and innovative field such as AM. Reviewing these could also yield interesting insights although this was beyond the scope of this systematic literature review. Another limitation is that due to the usage of the SCOR framework, the consumer perspective is mostly missing. End users constitute an important factor for the deployment and adoption of AM and its services as described by Halassi, Semeijn, and Kiratli (2019). Further, AM can be regarded as a parent term for various, partially very different, technological approaches. Different AM approaches develop at different speeds and might also impact the SC in slightly different ways, an aspect that has not been fully accounted for in this study.

Conclusion

This systematic literature review enables the identification of characteristics and main trends in the literature investigating the impacts of AM on different areas in the supply chain. Benefits and challenges concerning the application of AM are pointed out and based on that, future lines of research are identified.

The descriptive analysis characterised the existing literature in the field of AM, and it includes interesting findings such as the fact that benefits of AM are much more frequently discussed than challenges. The qualitative analysis, on the other hand, provided an in-depth investigation of supply chain specific impacts of AM that show that there is a strong focus on design aspects, whereas other characteristics are neglected in the scientific discourse. In the overview of AM applications in different industries, the primary industry drivers for AM application were identified. Significant interest in AM was found in the aerospace industry as well as in the production of industrial and consumer goods. The discussion section focussed on critically assessing the statements made in the literature.

The academic contributions of this study include the mapping of relevant literature in the field and the identification of future research lines that can help guide the scientific community. Managerial implications that can be derived from this study are manifold. The supply chain dimension specific analysis concerning the benefits and challenges in the qualitative analysis and discussion section provides valuable insights for managers concerning the adoption of AM technology. Additionally, an industry-related overview allows an easy location of primary issues and relevant literature in this regard.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendix A. Research dimensions and descriptions

Name	Description
Postdefined dimensions	Research dimensions that were defined after an initial screening of the selected articles. They reflect the main issues as identified in the selected literature and were not already covered by the predefined dimensions. Identified through auto-coding, pattern-finding, and word frequency functionalities in NVivo, framed by the authors.
Cost	Cost implications of AM.
Environmental sustainability	Environmental implications associated with the adoption of AM with a focus on the sustainability perspective.
Maintenance	Impacts of AM on the SC concerning service quality, maintenance, spare parts management and novel service approaches that arise through new possibilities as generated by AM.
Product design	Product design and redesign not supply chain design or mere IT based design discussions. This includes geometrical, optical, material, surface properties. Also includes customisation, personalisation and co-creation.
Logistics	Implications of the adoption of AM on logistics. This includes transportation, inventory, commissioning, inbound- outbound, handling (including taxes and duties).
Predefined dimensions	These research dimensions were identified prior to analysing the relevant literature and aim at answering the research questions.
SCOR framework	An integrated supply chain management process separated into the following dimensions.
Plan	Assessment of supply resources, aggregating and prioritising demand requirements, plan production, inventory, material requirements, and capacity requirements.
Source	Obtaining, receiving, inspecting, testing and purchasing of raw materials or finished goods.
Raw material	Supply chain implications of AM considering the usage and handling of raw materials.
Work-in-progress	Supply chain implications of AM considering the direct creation and handling of work-in-progress goods including parts consolidation.
Finished goods	Supply chain implications of AM considering the direct creation and handling of finished goods. Especially direct digital manufacturing.
Deliver	Picking, packing and configuration of products, the consolidation of orders, and the outbound transportation processes with shipping, import and export. It also includes managing accounts receivables and the customer database.
Return	Defective, warranty, and excess return, disposition and replacement including scheduling and administration.