logistics

Article

Additive Manufacturing: A Game Changer in Supply Chain Design

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Abstract: Additive Manufacturing (AM) is a digital manufacturing technology that enables companies to rethink their supply chain (SC) design. By means of literature synthesis, we build new knowledge about the mechanisms AM induces to improve SC design and performance, as well as the disruptive changes AM can cause. We investigate opportunities to optimize SC design for manufacturing purposes by exploiting the characteristics of AM, e.g., its freedom in terms of shape design and complexity and the absence of a need for object-specific tools. We study the roles of demand, assortment, IT systems, sourcing, manufacturing, knowledge, warehousing, and transportation, and explore the effects and tradeoffs on various SC performance outcomes, including cost, assets, and responsiveness. The contribution of this article is twofold. First, through literature synthesis, we construct six AM SC mechanisms that can be used in SC design to achieve desired SC outcomes for AM production applications in certain (business) contexts. Second, we identify the disruptive 'game-changing' effects of AM for SC stakeholders. This knowledge can be used by other researchers to develop further research. Moreover, general and logistics managers can use the results to fully exploit the potential of AM for designing much improved supply chains. Innovators and policy makers can use the results to understand the potential game-changing consequences of AM.

Keywords: additive manufacturing; supply chain design; literature synthesis; mechanisms; innovation; disruption

1. Introduction

We live in dynamic times. Swab [1]—founder and executive chairman of the World Economic Forum—argues that the world is at the frontier of the 4th Industrial Revolution. Technology—e.g., mobile supercomputing, artificial intelligence, robots, and autonomous vehicles—changes at an ever-increasing pace, and transforms societies. Over the last few decades, these, and other factors—such as rapid growth of the world population, customer awareness, sustainability issues, and globalization—have all created new performance challenges for supply chains.

A supply chain (SC) is a set of three or more organizations or individuals directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to the customer and vice versa. Creating customer value, lowering costs, increasing responsiveness, co-creation, managing demand variations—and ultimately creating a competitive advantage—are the overriding goals of SC management [2]. SC design is a strategic issue for any company [3], and can be defined as a set of decisions regarding structure, partners, locations, capacities, and systems for SC management [4]. We suspect that, due to these new challenges, traditional SC concepts can no longer support managing the trade-offs between supply chain objectives. By applying new technologies, multiple objectives—in this article called SC outcomes [5]—may be achieved concurrently (e.g., the triple bottom line). One of new technologies is Additive Manufacturing (AM), also known as 3-D printing, Rapid Prototyping (RP), Rapid Tooling (RT), Rapid Manufacturing (RM), or (Direct) Digital Manufacturing [6,7]. What these makes AM unique is that material is added layer-by-layer, contrary to subtractive, traditional or tool-based manufacturing, where the starting point is a solid piece of material and pieces of material are subsequently removed. According to Rayna and Striukova [8], the adoption of AM for prototyping and tooling applications has reached a stage of maturity, contrary to AM applications for (regular) manufacturing and 'at home' fabrication.

Current academic literature is unclear about the implications of AM for supply chains. Within the management literature, AM is viewed as being disruptive to existing business models and supply chains [9–12], while there is more ambiguity in the academic literature. Some authors consider AM to be a useful production technique for particular products [13,14], while Steenhuis and Pretorius [15] suggest that AM will result in incremental as well as disruptive innovation. Incremental innovation may occur in situations where AM replaces or complements existing traditional manufacturing, while disruptive 'game-changing' effects [16] may occur when, for instance, manufacturing moves from central factories to individual households.

Research on the implications of AM on SC design is still in its infancy, and Waller and Fawcett [17] have encouraged researchers to publish studies which address this particular gap in the literature. Moreover, Holmström, Holweg, Khajavi, and Partanen [6] have identified 'SC structure' as key to their research agenda. In this article, we focus on the potential of AM for designing vastly improved supply chains and, in doing so, intend to fill this knowledge gap.

In this article, we analyze how the unique characteristics of AM influence SC design, SC outcomes and SC mechanisms—and ultimately disrupt the game of the SC players. In particular, we focus on the manufacturing applications of AM. More specifically, we explore SC mechanisms, which we define as the link between SC design elements and SC outcomes. SC mechanisms determine how management decisions influence the performance of supply chains. Examples include economies of scale, customization, and postponement. The unique characteristics of AM in supply chains may induce mechanisms that enable adjusted supply chains design, improving SC performance outcomes and changing the game of (disrupting) the position of SC stakeholders. In this article, we show that AM can alter these mechanisms significantly. For instance, AM's freedom in shape design may take 'customization' to the next level. Using a digital design and a customer co-creation platform allows customers to become (co-) developers, and makes it possible to provide affordable personalized healthcare products to a larger share of the population [18–20]. AM may also change 'postponement'. Digital inventory may replace physical inventory and products may be produced on-demand, enabling in-situ and on-demand manufacturing in difficult-to-reach locations. Product availability and responsiveness may increase, and costs may decrease. Some existing SC participants may become redundant, e.g., customs and transportation [14,21,22].

We used the so-called CIMO logic to carry out a thorough and fine-grained literature synthesis in order to cumulate existing knowledge and generate new knowledge about AM SC mechanisms [23,24]. This systematic review has allowed us to construct six AM SC mechanisms—and is the first contribution of this article. We also explore the conceptual relationships between SC design and outcomes in various contexts, and explain the differences between these new mechanisms and more 'traditional' SC mechanisms. Our second contribution is determining how these improved SC outcomes can disruptively change the game of SC stakeholders. The method we used for literature synthesis may serve as an example for other researchers who seek to generate new knowledge about SC mechanisms and disruptions caused by these new technologies. Moreover, managers can use the results of this literature synthesis to exploit the potential of AM when designing vastly improved supply chains, while policy makers and innovators can use the results to improve understanding of the potentially game-changing effects of AM.

2. Contemporary Developments in SC Design

To set the scene, we first discuss contemporary developments in supply chain design. SC management overlaps with many other (management) fields, e.g., human resource management and information technology, and has porous and diffuse boundaries. To standardize definitions and enable benchmarking of processes and performances, the APICS organization developed the Supply Chain Operating Reference (SCOR) model [25]. This model uses the following categories—plan, source, make, deliver, return and enable—which together describe the steps (and decisions) involved in SC design. SC designs influence the 'SC outcomes' in terms of performance, and further elaboration on this topic will follow in Section 3.1. According to Fawcett and Waller [16], the SC design is of strategic importance to ensure a firm's competitive position. SC decision makers must determine the right partners, roles, and relationships, in order to build a winning organization. SC designs are influenced by—and have to deal with—contemporary developments. The rise of information technology (IT) is a major disrupter of SCs. Examples include big data and predictive analytics, AM, autonomous vehicles and borderless SCs [16]. Next, we discuss disrupters and the impact on SC design in more detail.

As a consequence of the rise of the internet in the last few decades, traditional shops have largely been replaced by web shops. Several steps in the SC have been removed causing 'disintermediation' [26] and changes in the roles, knowledge and skills of people in the chain (e.g., from sales person to warehouse associate). Changes also occur in transportation modalities (e.g., truck deliveries to shops being replaced with at home delivery with vans), and in facilities (e.g., shops being replaced with distribution centers). Some tangible products have been turned into intangible products, for example video tapes, DVDs, vinyl, CD's, and books sold or rented out in shops have been converted into streaming platforms or e-books, thus removing and changing SC steps. Other tangible products can now be accompanied by (digital) service products—a process called 'servitization', which changes supplier and customer relations [27].

The quest for digitization, however, continues. A 'digital SC' is defined as 'a smart, value driven process, generating business value with novel and technological and analytical processes' and including e.g., augmented reality, cloud computing, sensor technology and internet of things [28]. Moreover, automation and robotization reduce the dependency on human resources and can potentially increase SC speed and reduce SC cost [29]. The development of blockchain technology is still immature but can potentially eliminate administrative and control tasks, thereby simplifying SC designs (again disintermediation) and reducing cost [30]. Internet technology-based platforms arise in line with 'the platform economy' [31]. Production capacity or transportation capacity can be shared by multiple customers. For example, the platforms Uber Freight and Pamyra enable sharing transportation capacity, which improves resource utilization, and reduces cost and footprints.

Customization is another trend. In the early days of mass-manufacturing, the amount of choices a customer could make were limited: According to Henry Ford, you could order any color T-Ford you like—as long as it was black. However, due to rising competition and customer expectations, the customer order decoupling point (CODP) has moved upstream, and the amount of options for customers has become unlimited, allowing for the creation of mass-customization. Mass-customization is a marketing and production concept used to create personalized products based on product modularity. It blends adaptability (the ability to produce customer specific products) with the low per unit cost of mass-manufacturing [32]. Postponement delays the production decision until the customer order is received [33,34]. Economies-of-scale requires that expensive (specific) tools are amortized over long series, but mass-production has limited flexibility and requires high inventories [35]. Lean manufacturing [36] and Single-Minute Exchange of Die [35] overcome some of these disadvantages and hence enable mass customization and personalization. Internet supported platforms allow customers to become increasingly involved in the design process and to 'co-create' [17] and take over tasks that used to be designated to designers and developers at companies.

The final trend we discuss is the sustainability trend. SC design meant to 'close the loop' focuses on the 'return' element of the SCOR model, and aims to reduce footprints, pollution, and resource scarcity [37]. This can result in benefits over the product lifecycle such as the reduced fuel consumption of light-weight products for, e.g., aerospace and car applications. The Paris climate treaty of 2015 has boosted awareness of the effects of (carbon) footprints on climate change. Sustainable supply chain design focuses on balancing the triple bottom line of profit, people, and planet, and addresses issues such as corporate social responsibility, e.g., child labor [38].

3. Methodology

This article describes the first phase of a larger research project—which includes empirical research—on the impact of AM on SC design. Conducting a thorough literature review is considered to be a good way of identifying the knowledge previously created. Systematic literature review (SLR) approaches have been recommended as they can find evidence for the clarity, validity, and auditability of the research—or, in other words, show that the findings are grounded [39]. According to Tranfield et al. [40], SLR can help to build a body of knowledge and provide a reliable basis for decision making. Pawson [41] has advocated taking literature reviews one step further by not merely summing-up existing literature, but rather synthesizing existing studies in order to enhance the generalizability of qualitative research. Since little theoretical knowledge exists in our field, our goal was to synthesize existing studies and develop new knowledge for designing supply chains using AM, therefore contributing to improved SC performance. We followed the general guidelines on SLRs provided by Booth, Sutton, and Papaioannou [39], and complemented these with the SCM specific guidelines provided by Durach et al. [42], using their recommended sixth step approach. Sections 3.1–3.6 through 3.6 explain these steps in more detail. Note that the fourth step (literature analysis and synthesis, Section 3.5) comprises more than usual, since we accumulated knowledge in order to create new knowledge by constructing six AM SC mechanisms, which are further explained in Section 4.2. The new knowledge we built (the AM SC mechanisms) from theory can be described as propositions that need to be verified using empirical research. However, this verification is not within the scope of the present article.

3.1. Initial Theoretical Framework and Question Formulation

Prior to defining the research questions, Durach, Kembro and Wieland [42] recommend that an initial theoretical framework is developed, specifying the scope of the unit of analysis. Our analysis is primarily about how SC designs, including the use of AM, influence SC outcomes. It identifies the two major theoretical components: SC design and SC outcomes. In order to build the theoretical framework, we used the CIMO framework of Design Science Research (DSR) [24], as suggested by Booth, Sutton, and Papaioannou on p. 87 in Reference [39]. In line with Mulder [43], and Tanskanen et al. [44], we used DSR's CIMO reasoning chains as a framework for a systematic review of the selected articles.

The logic behind this structure is that, in order to achieve the desired Outcome (O) in a certain Context (C), Intervention (I) might be effective, and needs to be validated in the field [45]. Pawson and Tilley [46] added the issue of causality by conceptualizing the Mechanism (M) that is activated by the intervention and delivers the outcome. Together, this creates the CIMO structure [23,47,48]. In our case, in a particular context (C), an SC design, including AM (I), leads, via certain mechanisms (M), to certain SC outcomes (O). We will now explain these elements in more detail. Context: This describes the business environment in which the particular supply chain operates. Intervention: We defined the design of the SC, including the application of AM, as the intervention, and used the SCOR (Supply Chain Operations Reference) model elements plan, source, make, deliver return and enable [25] as an overall structure and integrated the SC design involves choices related to capacity and position of manufacturing and warehousing facilities, assortment, sourcing, transportation modalities, and information systems [4]. Mechanism: In DSR's CIMO logic, mechanisms connect interventions with outcomes, in a given context [24]. In line with this, we define AM SC mechanisms in the following way:

"An AM SC mechanism links the SC design elements (including AM) with the SC outcomes in a given context"

SC mechanisms determine how management interventions can influence the performance of supply chains. According to van Aken, Chandrasekaran, and Halman [24], there is no straightforward way to determine these mechanisms. We chose to cluster the determined CIMO reasoning chains and in a creative, iterative process, assigned AM SC mechanisms. The mechanisms we identified—resulting from our literature synthesis—constitute one of the two main contributions of this article. We present them in Section 4 and compare them to equivalent SC mechanisms that existed prior to AM, e.g., mass-customization and postponement. Outcome: We define 'outcome' as the SC performance outcomes. The SCOR model [25] defines five supply chain outcomes: cost, assets, responsiveness, reliability, and flexibility [49]. According to Melnyk, Davis, Spekman, and Sandor [5], the supply chains of tomorrow must deliver varying degrees of six blended outcomes—in this scenario, security, sustainability, and innovation are added to the traditional outcomes of cost and responsiveness. We used the outcomes of both sources in this article. In line with Holmström et al. [50], we also checked for other, unintended consequences (side effects). These unintended outcomes may, for example, include cost increases for large series, high energy costs, or a larger carbon footprint.

Together, this results in our initial theoretical framework, as presented in Figure 1.

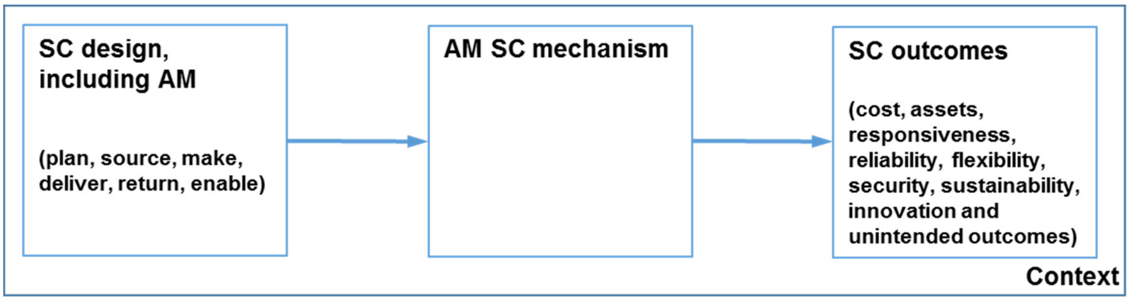

Figure 1. Initial theoretical framework.

The main objective of this study was to investigate how AM can improve SC designs for manufacturing applications. More specifically, we wanted to develop mechanisms to explain the relationship between AM SC design and outcomes. To this end, our research questions were:

1. In which contexts are AM supply chains used, how are they designed, and how do they perform?
2. What AM SC mechanisms for manufacturing applications can be constructed and what are the conceptual relationships between intervention (I) and outcomes (O) in various contexts (C)?
3. What are the disrupting effects of using AM supply chains for the SC actors?
4. How are AM SC mechanisms related to 'traditional' SC mechanisms?

3.2. Identifying the Characteristics of the Studies

In this phase, the inclusion and exclusion criteria are defined by assessing the contribution to the theoretical framework [42]. In order to guarantee high quality information, we only included scholarly peer reviewed articles and therefore excluded books and grey literature. While acknowledging that this is an innovative field that is developing at a fast pace, and academic literature often lags behind (due to the relatively long throughput time), we felt that only including high quality sources was preferable to including other (grey) sources, despite the fact that they may have provided some valuable insights. We did not apply time-restriction parameters, nor did we limit ourselves to articles in predetermined research fields, or exclude certain types of articles (e.g., empirical). For practical reasons, only sources written in the English language were used.

To synthesize the potentially relevant literature sample (discussed in Section 3.4), we determined that the selected articles should contain one or more of the context, intervention, or outcome elements, as defined in the theoretical framework presented in Section 3.1.

3.3. Retrieving Samples of Potentially Relevant Literature

In this step, potentially interesting literature is obtained through rigorous searches. We first identified the right key words and considered the breadth of the SCM field to determine the synonyms. In order to reduce retrieval bias [42], the researchers discussed the search terms and iteratively improved them during initial searches. This resulted in the key words presented in Table 1. The selected words were connected via AND/OR Boolean logic in order to find suitable articles. While recommended, we did not apply quality parameters (e.g., only include highly cited articles) in order to reduce publication bias [42].

Table 1. Key words.

Supply Chain Design	Additive Manufacturing
Supply Chain OR Supply Network OR Logistic OR Value Chain OR Network Design	Additive Manufacturing (AM) OR 3D Printing OR 3 Dimensional Printing (3DP) OR Rapid Manufacturing OR Rapid Prototyping OR Stereo Lithography OR DDM OR Digital Manufacturing OR Solid Free-form OR Layer Manufacturing OR Rapid Casting (RC) OR Rapid Tooling (RT) OR Material Deposit Manufacturing OR Material Addition Manufacturing OR Additive Layer Manufacturing

Using the search terms and characteristics, we performed several searches in the period between October 2016 and January 2018. During that period, the list of articles was updated several times in order to include the latest developments. We used online university software, which provided access to various databases including Emerald, Science Direct, Web of Science, and Google Scholar. This resulted in 503 unique articles and conference papers which were transferred to Endnote. The oldest article found dates from 1993.

3.4. Synthesizing Samples

The abstracts of the 503 articles were reviewed on the basis of whether they included the context, intervention, and outcome elements of our theoretical framework (Figure 1). In case of doubt, the full content of the article was scanned for relevance. This led to the exclusion of 456 articles. We found that our search terms also directed us to non-relevant articles. These articles were of a technical nature, for example, they included a discussion only of AM technology, or a technical discussion of AM print materials, or digital modelling (not AM-related) or SC modelling (e.g., for simulation, but not AM-related). To prevent inclusion criteria bias [42], and in order to be transparent, the reasons for exclusion were registered in a file. The remaining 47 articles were read in full. While reading the articles, we checked the citations (snowballing), a useful method for building up a good body of literature and identifying studies that may have been missed via bibliographical searches on p. 121 in Reference [39]. This resulted in 13 additional articles being added to the full article review. Moreover, during the peer review process, our attention was drawn to one additional article which we also added. The absence of these 14 articles in the original searches can be explained by the fact that SCM is a broad and permeable science [42] and the authors of these articles did not consider the articles to be SCM relevant (although they did in fact prove to be relevant). Due to practical constraints, we did not involve multiple researchers and a blind selection process, although this has been recommended by Durach, Kembro, and Wieland [42] as a way of preventing selector bias.

In the articles that we fully reviewed, the relevant SC information was often missing, hidden or vague, which is in line with the complex issues that arise in organization and management [23]. The articles originate from 27 different journals, encompassing a broad range of categories (Table 2), which reduces the chance of missing crucial elements. It is important to note that, although all our selected articles have been peer reviewed, most are based on experiential knowledge, and while this can provide us with valuable insights, only relatively few are based on rigorous empirical evidence.

Table 2. Journal categories.

Journal Categories	Number of Articles
Manufacturing/Production/Technology	27
SC/Logistics/Operations Management	12
Information Systems	5
Business/Economics	5
Social/Ethics	4
Ecology/Energy	4
Materials/Engineering	2
Unknown	2
Total	**61**

3.5. Analyzing and Synthesizing the Results

Research synthesis (or research integration) refers to finding similarities in related research, while at the same time taking differences into account, a process which potentially leads to generalization [51]. This step itself consists of two parts. First, a coding scheme is developed based on the initial theoretical framework. The second part then involves analyzing and integrating the results.

In line with this, and based on our initial theoretical framework, we developed a two-step coding scheme. The main codes were based on theory and are listed in column 1 of Appendix A 1. We allowed for open coding. The detailed codes that emerged during analysis of the articles are listed in column 2 of Table A1 in Appendix A.

For the main codes related to 'AM SC context', we differentiated between industry and product type [52], sales channel [53], product life cycle phase [54,55], and demand characteristics [56]. We also included barriers to AM implementation, which may impede the far-reaching diffusion of AM [57].

For the main codes related to 'SC design intervention', we used the SCOR elements (plan, source, make, deliver, return, enable). In the SCOR element 'plan', we included stock-keeping-unit (SKU) choices and other SC planning related interventions, e.g., changing order of SC steps or elimination of SC steps. In 'source' we included the sourcing partner choices. In 'make', we included the Customer Order Decoupling Point (CODP) [58,59], the positioning of AM in the chain (SC configuration) and the positioning of AM machines in the operation. In 'deliver', we included the impact and choices related to inventory keeping, warehouse and warehouse equipment, as well as choices related to transportation (modalities). In 'return', we included returns management [37], with disassembly, recycling, assets' lifecycle, waste materials and pollution, and, finally, in 'enable' we included choices related to IT systems and the impact on people working in the chain. Note that the main codes (overall categories) were developed from theory, while the aforementioned detailed codes (subcategories) were developed in an iterative process while reviewing the literature. For the main codes related to 'SC outcomes' we used the categories as defined in the theoretical framework (Figure 1). We did not use coding for the 'mechanism' since this is a result of our synthesis (this will be further explained in Section 3). While we coded the literature to the best of our abilities, for practical reasons we were not able to use multiple independent coders to prevent within-study bias, as recommended by Durach, Kembro and Wieland [42].

While analyzing the 61 articles and developing the coding scheme, the existing published research was synthesized into 'means to end statements' or 'CIMO reasoning chains' [45] with the aim of determining the main mechanisms that turn interventions into outcomes. The mechanisms we developed are explained in Section 4.2. Again, due to practical constraints, we were unable to conduct parallel and blind synthesis involving multiple researchers, as recommended by Durach, Kembro and Wieland [42] as a way of preventing expectancy bias.

3.6. Reporting the Results

The results are reported in Section 4.

4. Results

We present the information in the following sections. In Section 4.1 and Appendix A, we present the results of the literature analysis. In Section 4.2, we outline the results of the literature synthesis, by constructing the AM SC mechanisms and the conceptual relationships between SC design and SC outcomes.

4.1. Descriptive Results

This section refers to Research Question 1. Since this contribution relates to the literature synthesis (Section 4.2), we merely highlight the most frequently mentioned findings related to the context (C), intervention (I) and SC outcomes (O) of the literature study, while Table A1 in the Appendix A contains the complete findings. The Mechanisms (M) are presented in Section 4.2.

AM was first adopted for (rapid) prototyping and (rapid) tooling in the 1990s, and by now the related supply chains are mature. The next phase—rapid manufacturing or (direct) digital manufacturing—started in the late 2000s when costs lowered and manufacturing quality improved sufficiently. The last phase—home fabrication by consumers—started in the early 2010s and is in a very early phase of development [8].

The remainder of this discussion focuses on the RM or DDM phase. Our findings show that AM is used in many industries and for many different applications e.g., aeronautics, medical applications, (car) manufacturing, consumer products and construction. Frequently mentioned applications include spare parts, components and assemblies for both manufacturing and maintenance purposes. In the current state of development, AM is often used to cope with fluctuations in demand and for (very) low demand, or for the production of single units. For manufacturing purposes, many barriers still exist related to quality, materials, processing, (lack of) knowledge, a lack of clarity about IP, and a lack of legislation/regulation.

The use of AM may make supply chains shorter and simpler, and the order of steps may change. Finished goods may be replaced with raw materials, and digital inventories may replace a large assortment of physical inventories. Fewer machines, buildings, and tools may be required. Online platforms may be required for the (co-) creation, storage and retaining of digital files. There may be reduced demand for raw materials which can be sourced from the same (local) source. This reduces dependency on component suppliers, and increases dependency on material suppliers. Desired scale-economies may initiate outsourcing to AM service providers. AM can either replace or complement traditional-manufacturing, the CODP may shift, and central, distributed and mobile SC configurations may exist. People's roles may change and new knowledge may be needed. Transport modalities may also require change and there may be a reduced need for warehousing.

AM mainly reduces SC costs by reducing inventory, raw material, production, assembly, transportation and operational costs. Moreover, there may be a reduced need for assets, and, for small series, responsiveness may improve. Quality, reliability, flexibility, sustainability and innovativeness may also improve. Unintended outcomes may also occur, e.g., data transfer security risks may arise as a result of knowledge leaks. For larger series, product costs may be higher and product availability may be slower. According to the analysis, the key SC decisions for designing AM SCs concern:

- AM equipment, including decisions about the positioning of machine(s) in the SC; AM allows unlimited freedom of (shape) design in the manufacturing of light-weight products with integrated functions, requiring no object specific tools (to be amortized over long series). It also allows production of different shaped products in the same production run;

- Supply of raw materials products are produced from the same source material (e.g., powder). Material is (relatively) easily transported to (local) AM production;
- Design for AM knowledge are required to realize the full potential of specific digital designs;
- Customer platforms enabling ordering and/or co-creation between designer/customer and manufacturers;
- System for the storage of designs enabling design reuse and/or adaption.

The above-mentioned SC decisions are key for constructing the AM SC mechanisms outlined in the next section.

4.2. Constructing AM SC Mechanisms

This section refers to Research Question 2, and relates to the first contribution of this article. According to CIMO, interventions lead to outcomes induced by mechanisms. In this section, we outline six AM SC mechanisms that were constructed as new theory from our literature synthesis. The related figures show the conceptual relationships between the SC design interventions and outcomes for each mechanism.

4.2.1. Co-Customization Mechanism

The co-customization mechanism originates in the mass-customization mechanism in traditional manufacturing. Co-customization (Figure 2) goes one step beyond. It is enabled by an intervention of (a) AM's unlimited shape freedom in terms of shape design, (b) system storing designs to share and re-use [60], and (c) a customer platform enabling co-creation [8,17] between designer (customer or representative) and manufacturer. It personalizes output by means of offering unique products and customer involvement and improves quality through iterations. It seamlessly serves the needs of the customer with further-improved or new product innovations, even for products that were previously impossible to make [61]. AM enables the production of products with high customization and high complexity at low or zero added cost [62]. Design iterations enable improvement updates after every single unit [6]. The classic distinction between the product lifecycle phases 'design' and 'manufacturing' becomes permeable; the phases are integrated. In fact, every manufactured product is potentially a new prototype where what has been learnt from previous designs can be integrated into future designs.

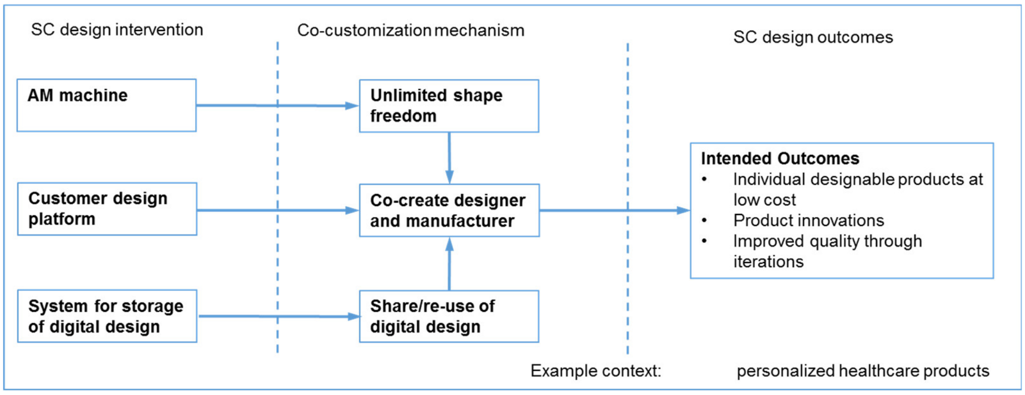

Figure 2. Co-customization mechanism.

Applications of this mechanism are found in customized healthcare products [18–20,62–64].

4.2.2. In-Situ & on-Demand Mechanism

The in-situ & on-demand mechanism uses elements of the traditional 'postponement' mechanism but offers more options. When making the change from traditional manufacturing to AM, Make-to-Stock (MtS) may become redundant, and Make-to-Order (MtO) or Engineer-to-Order (EtO) may become economically feasible. In this case, the CODP moves upstream, however, due to the elimination of SC steps, far less so than in traditional manufacturing. Effectively, for MtO and EtO, the CODP shifts downstream towards the customer, while for MtS it remains the same. In other words, CODPs now almost concur, whereas they were miles apart in the past.

The in-situ and on-demand mechanism (Figure 3) is enabled by an intervention of (a) AM requiring no object specific tools and a shorter SC with reduced steps, (b) systems to create (scan) or store designs allowing design-sharing and reuse, and (c) local supply of one source of raw materials. This allows manufacturing in distributed locations [65] near or on-site at the customer location, from one source of raw material, reducing transportation requirements and improving order lead-time and product availability.

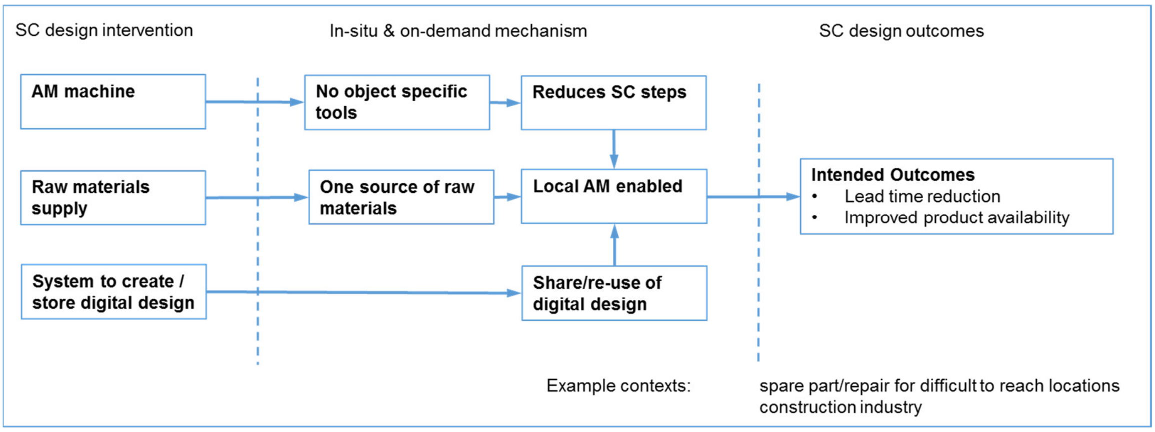

Figure 3. In-situ & on-demand mechanism.

Applications of this mechanism have been reported for difficult-to-reach locations. De la Torre, Espinosa, and Domínguez [21] reported that AM of truck spare parts for humanitarian aid can improve truck availability as a result of bypassing customs, and reduce potential theft, bribery and transportation issues. To obtain the digital file, scanning or cooperation with the truck manufacturer may be required. Ford and Despeisse [66] have mentioned the in-situ repair of turbine blades, and Kothman and Faber [67] have described the on-site production of parts allowing for lighter designs and reducing SC steps. Moore et al. [68] have described on-demand AM of coronary stents in operating room—potentially reducing the supply chain lead-time. Finally, Ryan et al. [69] have described mobile AM for spare parts production in difficult to reach locations and for the construction industry.

4.2.3. Shared-Economies Mechanism

Economies-of-scale is the traditional mass-manufacturing equivalent of our shared-economies mechanism. However, AM takes economies-of-scale to another level. When designing an operations strategy, process choices [70] are required. AM offers new options, since standardized processes can flexibly produce specialized products. Unique products—which, according to the product-process matrix of Hayes and Wheelwright [71], are traditionally produced in a jumbled flow (job shop)—can now be produced in a disconnected line (batches), traditionally reserved for small series of the same products.

The shared-economies mechanism (Figure 4) is enabled by an intervention of (a) AM with its unlimited freedom in shape design allowing various unique products to share one batch, (b) a customer platform allowing consolidation of orders, and the support of (c) a system that stores digital files. This leads to faster production and cost reductions for low demand products.

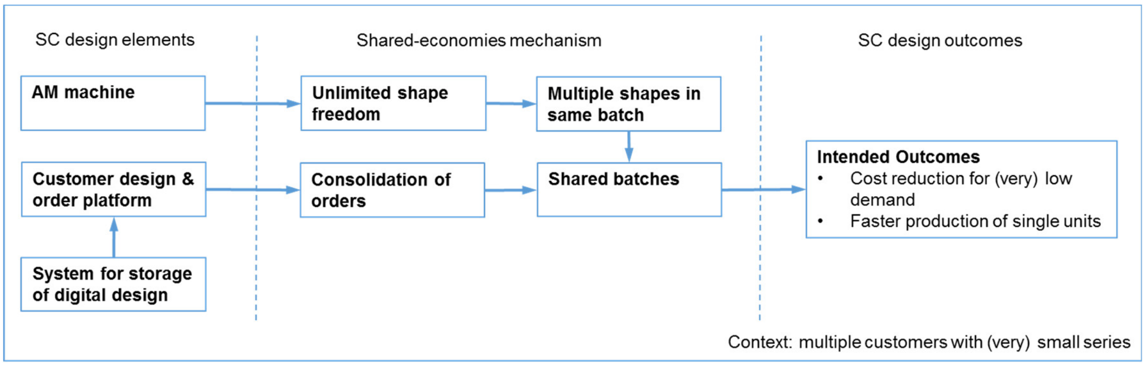

Figure 4. Shared-economies mechanism.

The absence of product specific tools makes amortization of expensive tools over long series of identical products unnecessary [6,61,72]. This is called the 'economies-of-one' concept [13,16], and can either coexist with economies-of-scale [73], or make it irrelevant [74]. Since the AM build chamber should be utilized efficiently, demand from various customers can be pooled and outsourced to an AM service provider who can have economies-of-scope in equipment and material purchasing, labor, and knowledge [13,75].

4.2.4. Digitized Stock Mechanism

AM enhances the possibilities of traditional postponement [33,34]. An AM SC allows digital inventory to replace physical inventory [14,22,62,76–78], transferring the differentiation decision physically closer to the point-of-use (hence downstream), but paradoxically, the CODP shifts upstream from MtS to MtO process wise.

The digitized stock mechanism (Figure 5) is enabled by an intervention of (a) AM requiring no object specific tools, (b) raw materials supplied from the same source in (c) a system storing digital designs to share/reuse. This allows differentiation at the latest moment and consequently results in replacement of a range of stock keeping units [14,76]. Moreover, it improves parts availability and reduces the need for inventory keeping.

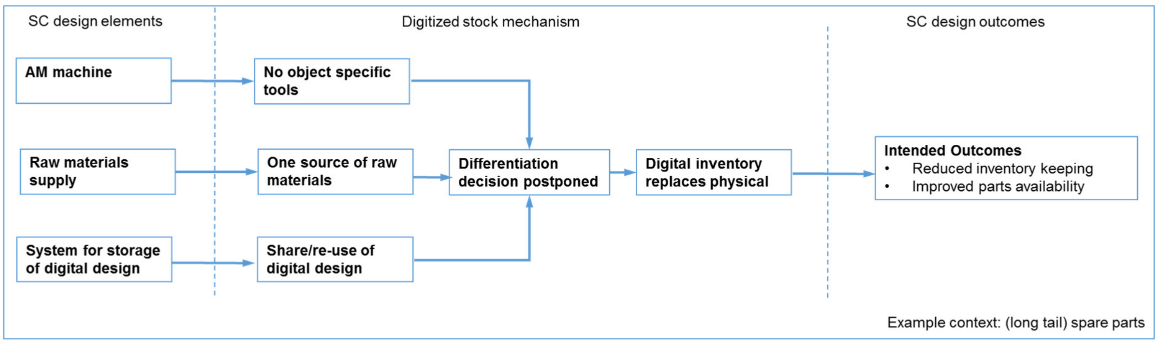

Figure 5. Digitized stock mechanism.

Applications of this mechanism include the production of spare parts [79,80] with very low demand or parts shortage [72,81]. Pérès and Noyes [14] have mentioned causes like destructed tools and company liquidation and Sasson and Johnson [82] have compared AM slow moving spare parts to 'the long tail'. Note that MtS is still possible with AM but that MtO and EtO become serious alternatives, as discussed in Section 4.2.2.

4.2.5. Buy-to-Fly Spin-offs Mechanism

The 'buy-to-fly ratio' is the weight of raw material bought, versus the material weight actually used in the part [73,83]. It is not a new concept, but AM enhances its potential and creates spin-offs.

The buy-to-fly spin-offs mechanism (Figure 6) is enabled by an intervention of (a) AM with its unlimited freedom in shape design, (b) specific AM design knowledge resulting in (c) a digital design. This combination allows production of light, complex and strong products—where less material is required during production, improving the 'buy-to-fly ratio'. At the same time, lightweight products create spin-offs during the product's life-cycle by reducing fuel consumption, carbon footprint and cost [73,83].

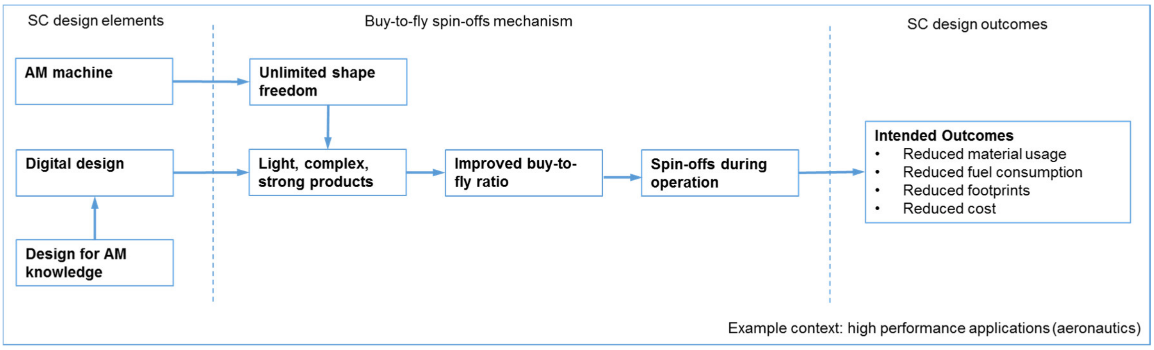

Figure 6. Buy-to-fly spin-offs mechanism.

Typical applications of this mechanism are found in lightweight and complex structures for low-demand, high-performance components and assemblies in the aeronautics industry [66,75,84].

4.2.6. Functionality-Integration Mechanism

Related to this mechanism is the SC disintermediation mechanism in traditional manufacturing, which constitutes the removal of steps in the SC and is often related to online transactions and e-commerce [26].

The functionality-integration mechanism (Figure 7) is enabled by an intervention of (a) AM with its unlimited freedom in shape design allowing integration of functions during the production process, (b) specific AM design knowledge resulting in (c) a digital design. The combination of these SC design elements allows for the production of products with integrated functionalities and the elimination of certain SC steps. In fact, production and assembly tasks reduce, resulting in increased SC speed and reduced costs.

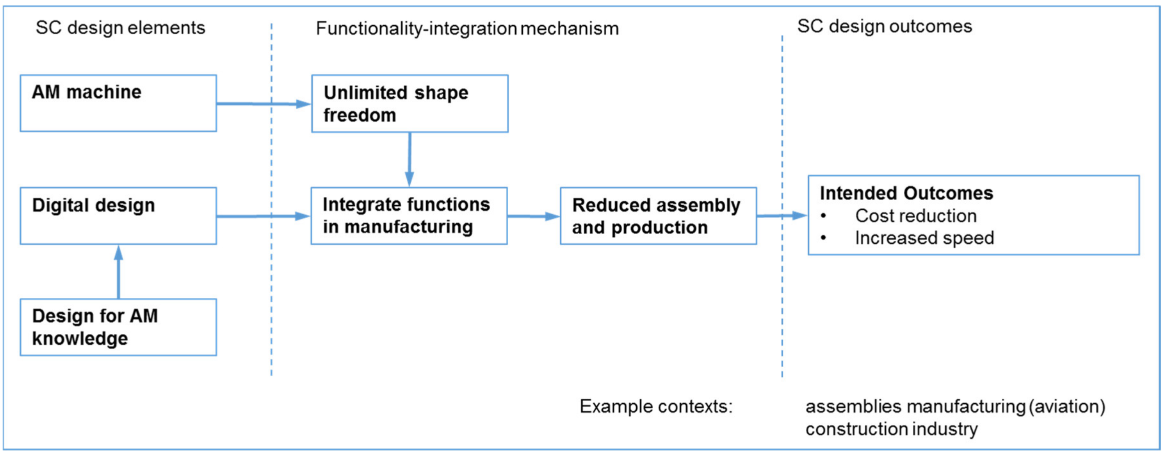

Figure 7. Functionality-integration mechanism.

Glasschroeder et al. [85] made a distinction between integration of mechanical functions (e.g., assembled parts inside), thermodynamic functions (e.g., integrated heating channels) and electrical functions (e.g., integrated conductive materials). Examples of this mechanism can be found in the integration of mechanical functions in assemblies [78,86] in the aviation industry [75], and in the integration of thermodynamic functions (cooling channels) in the construction industry [67].

4.3. The Game-Changing Effects of AM SC Design

In light of the 4th industrial revolution, managing supply chains and adapting their designs is a major challenge in a rapidly-changing world. This section answers Research Question 3, and relates to the second contribution of this article by identifying the game-changing effects of SC designs using AM, where a 'game-changer' disruptively changes the game between actors [16]. In line with Steenhuis and Pretorius [15], who have suggested that AM causes incremental innovation in one context, while being disruptive in another, we define the game-changing effects for the stakeholders per context and per mechanism, and underline the affected stakeholders.

In an AM SC 'co-creation', customers are actively involved in the design process—allowing them to become 'prosumers' [66,73,76]. Manufacturing may move from centralized factories to individual households, customers become developers, and manufacturers become entrepreneurs in the 'maker-movement' [16].

Once technological and regulatory issues have been solved, the impact of using this technology for medical device manufacturers and their suppliers may be extreme. Moore, O'Sullivan and Verdecchia [68] reported a test case where in-operating room AM of stents can shrink the SC lead-time from 150 days to 20 min. Individual companies lack the scale economies to efficiently utilize the AM equipment, and may outsource to regional printing centers who consolidate order volume from various customers [13,75]. Rogers et al. [87] identified 404 of these 'supercenters' already in existence in Europe, serving multiple markets. Flexible and less capital-intensive relationships may replace fixed relationships with machine suppliers.

In difficult-to-reach locations, due to factors related to poor infrastructure, geography, danger, customs, or bribery [14,21,22,62,69], manufacturing interruption may be expensive or late delivery may have negative consequences [88]. AM may enable local and on-demand AM of e.g., spare parts, which allows the bypassing of e.g., customs and transportation. Moreover, better local product availability may improve living standards in developing countries, exerting an influence on society as a whole. AM may be used for the manufacturing of surgical tools [19], for improving surgical procedures, reducing cost and improving patient well-being (relevant for hospitals and insurance companies). In-situ repair of equipment, e.g., turbine blades [66] may extend product life-cycle, improving equipment up-time, reducing cost, improving footprints, and disrupting the roles of manufacturers, repair-agents, customers, and society as a whole.

AM's ability to produce lightweight, strong and complex structures supports the manufacturing of lightweight components, for e.g., aeronautics applications [66,75,84], which in turn reduces fuel consumption and carbon footprint during operation, and reduces the need for raw materials, thus having a positive influence on society as a whole. Design-for-AM knowledge is a key requirement, and educational institutions need to adapt to accommodate this. Kothman and Faber [67] have outlined the SC benefits of AM for the construction industry in terms of integrating functionalities during manufacturing. This reduces SC steps, suppliers and cost, as well as increasing building speed and improving footprints.

We use the CIMO structure in Table 3 and extend this by outlining the related game-changing effects for the SC stakeholders.

Table 3. CIMO per mechanism and disruptive effects on SC stakeholders.

	Context	SC Intervention	Mechanism	Desired SC Outcomes	Disruptive Effect on Stakeholders
I	• Personalized medical devices	• AM machine • System for digital design • Co-creation platform	• Co-customization	• Highly customized products • Improved quality through iterative development • Improvement updates after every product produced • Improved responsiveness and reliability at lower cost	• Customers: become developers, actively involved in design process • Producers: become entrepreneurs • When AM reaches maturity: dramatic changes in competitive position • Society: affordable healthcare available for larger share of population
II	• Spare parts/repair • Difficult to reach locations • Construction industry	• Local AM machine • Local supply of raw materials • System for creation and storage of digital design	• In-situ & on-demand	• Lower cost of transportation, raw materials, and finished goods • Improved responsiveness • Improved product availability	• Customers: Increased customer service (healthcare) level • Customs: role changes due to potential bypassing • Society: reduced theft, bribery • Suppliers: reduced need for transportation • Manufacturers and repair agents: extended product life-cycle • SC players: elimination due to elimination of SC steps
III	• Multiple customers with (very) small series	• AM Supply Platforms • AM machine • System for digital designs • Customer platform	• Shared-economies	• Cost reductions for low demand • Faster production/availability of single units	• Customers: cheap, fast convenient products; increased risk for fake, low quality products • Designers: risk of knowledge leak • Manufacturers (existing): Reduced order volume • Suppliers: fewer fixed relationships with customers • OEM's: partnerships with AM supply platforms required • Society: new companies
IV	• Long-tail spare parts	• AM machine • Supply of raw materials • System for digital designs	• Digitized-stock	• Reduced finished goods inventory • Improved parts availability • Reduced transportation	• Suppliers: Reduced warehousing and transportation leading to reduced 3PL's • Society: Reduced need for personnel
V	• High performance applications (aeronautics)	• AM machine • System for digital design • Design for AM knowledge	• Buy-to-fly spin-offs	• Reduction of material cost • Reduction of lifecycle cost • Reduced footprints	• Engineers/educational institutions: design for AM knowledge required • Suppliers: reduced need for raw materials • Society: reduced footprints
VI	• Assemblies manufacturing • Aviation/Construction industry	• AM machine • System for digital design • Design for AM knowledge	• Functionality-integration	• Reduced production, assembly and raw material cost • Less assets • Reduced production & assembly lead-time	• Engineers/educational institutions: design for AM knowledge required • Suppliers: reduced SC steps reduces need for production/assembly equipment • Society: fewer SC steps reduces need for production and assembly personnel

5. Discussion

This section discusses the AM SC mechanisms we developed through systematic literature synthesis of 61 peer reviewed articles in Section 4.2 and the game-changers discussed in Section 3.3.

When using AM in SC design, traditional SC mechanisms may evolve to a more advanced level and vastly improve SC performance. Related to Research Question 4, Table 4 summarizes the traditional and the constructed AM SC mechanisms from Section 4.2. We note that mass-customization may become unlimited, production decisions may be postponed to the very last minute before use, stock-keeping may change from physical to digital, different shaped products may be produced in batches allowing economies-of-scale to become a reality for individualized products, buy-to-fly ratios may improve and create spin-offs during use, and integration of functionalities may reduce SC steps in line with disintermediation.

Table 4. Traditional SC vs. AM SC mechanisms.

Traditional SC mechanisms	→	**AM SC mechanisms**
Mass-customization	→	Co-customization
Postponement	→	In-situ & on-demand
	→	Digitized stock
Economies-of-scale/batches for identical products	→	Shared-economies
Buy-to-fly	→	Buy-to-fly spin-offs
Disintermediation	→	Functionality-integration

Several relevant points can be made here. First, although we present these mechanisms as single mechanisms, in reality, often a combination of these mechanisms will exist. This is in line with Hsuan Mikkola and Skjøtt-Larsen [33], who have proposed that mass customization and postponement are interrelated. For example, Kothman and Faber [67] have described in-situ and on-demand 3D-printed construction elements, with integrated cooling functionalities and using a highly-customized, co-created design, thus integrating three AM SC mechanisms.

Second, other SC mechanisms may exist. For example, Baumers et al. [89] have described a mechanism using the 'if you can't measure it, you can't manage it' paradigm. Here, the single-step nature of AM leads to a simplified SC, which leads to a simplified production energy consumption measurement. The minimum cost configuration makes producers adapt their SC design—which reduces energy consumption and thus improves SC carbon footprint outputs. Moreover, Holmström, Liotta and Chaudhuri [88] have identified two potential SC practices ('incremental product improvement' and 'dynamic SC redefinition and reconfiguration') that may be implemented in the future. However, since these practices have not yet been observed, they are not included in our synthesis. In principle, any traditional SC mechanism, e.g., dual sourcing or closed-loop supply chains, may be affected in the future.

Third, the mechanisms presented here appear to consist of multiple 'building blocks', which can be seen as the underlying characteristics of these six AM SC mechanisms, see Figure 8. Some of these building blocks originate in the technical (additive) nature of AM, while others are not AM technology specific. A comprehensive understanding of these individual building blocks, and how they combine, is essential to the design of improved supply chains.

Figure 8 shows a general conceptual model of an AM SC design using the CIMO structure and extended with the inclusion of potential game-changers. It is worth noting that the future is unknown, and some effects may or may not occur, while other, as yet unforeseen consequences, may also occur [50].

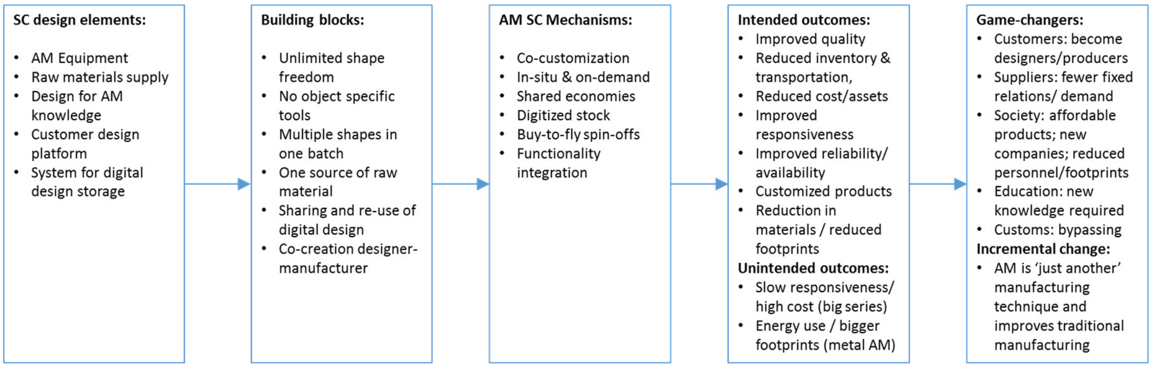

Figure 8. Summarized conceptual relationships.

6. Conclusions

This article contributes to the AM SC design knowledge base by building new theory and constructing six AM SC mechanisms to improve SC design. Furthermore, we compare these mechanisms to 'traditional' mechanisms used in the design of SCs for manufacturing purposes. This article also contributes to the innovation knowledge base by determining potentially game-changing effects of AM SC design. The method presented in this article can be used as an example for other researchers investigating the impact of new (other than AM) technologies on SC mechanisms and disruptions. While AM for manufacturing purposes is not yet fully mature, general and logistics managers should carefully observe the developments in AM—in particular the elimination of the barriers preventing the roll-out of AM. Once these barriers have been eliminated, this article can also be used by managers to fully exploit the potential AM has in terms of designing strongly improved supply chains. Alternatively, businesses can experiment with AM and find segments to 'cross the chasm' [90] between early adapters and early majority [91]. In such cases, a well-designed supply chain will be a key enabler for a successful business model.

Moreover, innovators and policy makers can use the results of this article to understand the possible game-changing effects of AM. Our findings can be summarized as follows.

(RQ 1) In the current state of development, AM is used for many different low-demand applications, e.g., in healthcare, (car) manufacturing and the aeronautics industries, and many technological and regulatory issues need to be taken into account. Supply chains may get shorter and simpler, and the sequence of steps may change. Raw materials may replace final products and digital files may replace physical products. Fewer raw materials may be used from just one source, thus changing relationships with suppliers. IT systems may be used for communication and design by customers, and new design knowledge may be required. AM may reduce SC costs and the need for assets. Responsiveness and other performance outcomes may improve, and on the other hand, unwanted outcomes may also occur.

(RQ 2) We synthesized existing theory and constructed six AM SC mechanisms. We explored their conceptual relationships, connecting SC design and SC outcomes. The resulting AM SC mechanisms are: (1) co-customization; (2) in-situ and on-demand; (3) shared-economies; (4) digitized-stock; (5) buy-to-fly-spin-offs; and (6) functionality-integration.

(RQ 3) We determined the game-changing effects of AM SC-design for the stakeholders. These include: customers turning into designers and manufacturers; reduced demand for suppliers and fewer 'fixed' relationships; affordable products for society; reduced need for personnel and reduced carbon footprints. Moreover, new businesses may appear and new (design-for-AM) knowledge may be required from educational institutions.

(RQ 4) We suggest that traditional SC mechanisms can evolve to an advanced level. Mass customization may become unlimited; production decisions may be postponed to the very last minute before use; stock-keeping may change from physical to digital; economies-of-scale may become a reality for individualized products; buy-to-fly ratios may improve and create spin-offs during use, and integration of functionalities may reduce SC steps in line with disintermediation.

Of course, our study has several limitations that give rise to further research. First, although we followed the research guidelines for SLR, it is possible that some bias may have occurred [42]. In step 4 (Section 3.4), due to practical limitations, we did not use a blind selection process in our peer review, nor did we use multiple researchers as a way of preventing selector bias. In addition, in step 5 (Section 3.5), coding and expectancy biases may have occurred when analyzing and synthesizing our results, since, again, we did not involve multiple researchers. Second, we only used peer reviewed articles to ensure that only high quality sources were included. However, AM is an innovative and fast-changing field, while the knowledge created in academic articles lags behind due to the relatively long processing times. The use of grey literature would have had the benefit of being more up-to-date. An additional reason for further research is that technological developments will continue to be made in AM. In addition, other new technologies, e.g., block chain, will provide new building blocks that may also cause changes to existing SC mechanisms, and result in disruptive effects for stakeholders. Consequentially, some may become redundant and new parties will emerge. New (combinations of) mechanisms may be found that lead to new SC solutions. Our literature synthesis enhances the current understanding of the evolution of SC design and the potential disruptions that can arise following the implementation of new technologies. In a final reflection on our literature synthesis, we emphasize that, although the selected articles have been peer reviewed and provide interesting insights, they are mostly based on experiential knowledge rather than empirical results. We recommend that future rigorous empirical research includes case study research using the DSR strategy [24]. In terms of both theoretical and practical considerations, there is still a lot of work to be done.

Author Contributions: V.V. authored the entire article. H.K. supervised the article by commenting, generating ideas and rephrasing sections.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Literature.

	AM SC Context	Authors
Industry	Aeronautics	[14,62,66,75,80,84,92,93]
	AM Service Providers	[8,87]
	Construction	[66,67,69]
	Utilities (energy, mining, oil)	[62,66]
	Food	[94]
	Healthcare	[8,18–20,62–64,68,88]
	Humanitarian aid	[21]
	Manufacturing	[66,78,79,82,86,95–104]
	Retail	[60]
Products	Components & assemblies	[62,66,67,78,82,84,86,92,98,100,101,104]
	Consumer products	[8,60,94,95,97,102,105]
	Houses	[67]
	Medical devices	[8,18–20,62–64,68]
	Spare parts	[13,14,16,21,22,62,66,79–81,93]
	Tools	[8,66,99,101]
Sales channel	Business-to-business	[6,13,14,18–22,60–64,66,68,72,75–78,80–84,86,89,93,96–101]
	Business-to-consumer	[67,73,76,94,95,102,105,106]
	Customer-to-customer	[60,61]
Product life-cycle phase	Development (prototyping)	[8,16,17,19,60,61,63,72,73,75,76,88,92,97,98,100,104]
	Both development and production	[6,20,62,67,68,72,78,81,87,94,101,102]
	Production	[6,8,13,16,18,19,60–62,64,66,67,72–79,81,82,84,86–88,95–97,99,101,107,108]
	Operation/use	[8,19,66,83,84]
	End-of-life (repair)	[14,21,22,62,66,80,93]
Demand	Low (or very low) demand/single units	[13,14,16,22,61,62,66,67,72,73,76,81,82,86,88,92,93,95,96,99,109]
	High demand fluctuations	[93,95]
	Immediate availability (not) required	[13,18]
	Systems difficult to access	[14,21,22,62]
	Product unavailability, shortage	[14,81]

Table A1. *Cont.*

	AM SC Context	Authors
Barriers	Product, (surface) quality, accuracy, durability, strength	[15,57,60,66–68,72,75,78,95,103,105,106]
	Material availability	[57,68,84]
	Material characteristics	[67,73,75,105]
	Material cost	[17,57,72,103]
	Lack of process automation	[66,67]
	Low production speed	[75,78,84,103]
	Reliability, stability of print process	[57,67]
	High machine cost, limited build sizes	[57,69]
	Limited process parameter control	[109]
	AM and AM design knowledge required	[20,57,61,73]
	Awareness and acceptance of employees, management and customers	[57,104]
	Lack of government support; cost calculation knowledge, vendor trust; management support; designers attitude; workers resistance	[103]
	IP unclear	[6,13,60,61,72,73,75,81,87,103,106]
	Missing legislation and regulations	[15,57,61,64,68,87]
	Liability and warranty unclear	[6,61,66]
	QA, testing and inspection missing	[13,61,66,67,73,75]
	SC Design Intervention	**Authors**
Plan	Range of SKU's replaced by one process	[14,22,62,72,76–78]
	Regular SC re-alignment required with increasing AM maturity	[110]
	Design-build-deliver paradigm shift	[73]
	Improved economies of scope in mass-production	[82]
	SC shorter and simpler	[6,22,67,68,76,79,81,84,107]
Source	Network of partners and cooperation with SC partners required	[20,21,73,75,87,111]
	Licencing agreements with OEMs	[87]
	Local supply of raw materials	[66,73,77,101,102]
	Shift from component supply to raw material supply; Reduced dependency on component suppliers; Reduced supply of raw materials	[66,67,72,83,101]
	Outsourcing of AM to service providers/capacity pooling	[13,72,75,81]
	Powerful raw material suppliers	[109]
	Reduced partners in the supply chain	[67]

Table A1. *Cont.*

	AM SC Context	Authors
Make	Engineer-To-Order/Make-To-Order	[6,13,14,16,18–22,60–62,64,66,68,72,76,79,81,87,94,95,101,102,107,108]
	Make-To-Stock	[13,18,80,93]
	Central AM configuration	[13,18,60,79,80,93,94,101,106,109]
	Distributed AM configuration	[6,8,13,14,21,22,57,60–62,66,68,73–77,80,87,88,102,105,112,113]
	Distributed manufacturing, central coordination	[60]
	Distributed manufacturing, central design	[20]
	Distributed scanning, central manufacturing	[87]
	Mobile AM	[69]
	Personal manufacturing (at site of consumer)	[8,69]
	AM production next to TM production line	[101]
	Reduced production steps and machines, assembly, facilities	[61,62,66,76,78,80,81]
	Versatile machine with standardized interface	[62]
Deliver	Reduced need for—and adaptions to—material handling equipment and distribution centers	[61,64,73,75,77,81,84,88,105]
	Reduced stock-keeping and shift to raw material stock-keeping	[6,13,17,60,64,66,68,72,76,79,81–83,88,93,96,102]
	Reduced transportation	[17,60,64,68,75,76,79,81,83,87,88,102]
	Change to digital file distribution	[13,21,66]
	Distribution of raw materials only	[66,67]
	Local distribution	[61]
	Production in-transit (mobile AM)	[69]
	At home printing as means of product distribution	[8]
	Transportation modalities require adaptions (e.g., bulk to fine)	[73,77,105]
Return	Enables extension of assets' lifecycle	[66]
	Enables internal recycling	[66]
	Enables use of recycled materials	[76]
	Reduced disassembly efforts	[78]
	Reduced waste material	[64]
	Reduced polution, landfill	[20,67,72,78]

Table A1. *Cont.*

	AM SC Context	Authors
Enable	Digital catalogue/database required for sharing and retaining of digital images	[13,19,66,73,74,87,101]
	Secure infrastructure required	[87]
	Combination with other electronic services	[14,107,108]
	Digital file co-creation by engineer and customer, design and customer integration through online platform	[60,61,66,73,88,101,102,113]
	Shift from conventional inventory management, using Bill Of Material, to individual tracking	[6,61]
	Online platform required	[60,84]
	Distinction between roles disappears; redistribution of tasks in the SC	[8,67,73,76]
	Reduced manual intervention; Reduced knowledge and skills required; Reduced need for personnel and overheads	[18,61,62,76,80]
	Production done by customer	[8,60,102,105]
	SC Outcomes	**Authors**
Cost	Reduced inventory cost (includes finished goods, raw materials, work-in-process, safety stock, obsolescence)	[6,13,17,18,60,61,64,66,67,72,73,75,76,79,81,82,86,88,93,95,96,101,102,109]
	Increased production cost (per piece); inefficient capacity utilization	[8,13,19,74,79,98]
	Reduced production cost (assembly, energy, set-up, efficiency)	[6,62,78,84,86,92,97,99,101]
	Products customized at no additional cost	[8,62,88]
	Increased transportation cost	[13,80]
	Decreased transportation cost	[17,60,64,66,67,75,76,79,83,87,102]
	Reduced final product cost (low volumes or complex products)	[15,88,105]
	Reduced lifecycle cost (includes operating, logistics, opportunity, warehouse, SC, material handling, warehouse cost)	[19,21,22,61,64,66,75,79–81,84,87,88,95,102]
Assets	Extended lifecycle	[66,88]
	Reduced parts for specific equipment (machines, facilities, tools)	[6,8,60–62,66,69,72,74–76,80,86,96–98,101,105]
Responsiveness	Increased time for production, assembly or repair	[80,95]
	Decreased production time (small series), assembly time; Decreased product development, (re) design, time to market	[6,8,13–16,18–22,57,60,62,66–69,72,73,75,76,78,80,82,86,88,92,96–101,113]
Reliability	Improved availability of products/services	[14,21]
	Improved product quality, reliability	[16,19,63,64,66,67,86,101]
	Improved consent and trust	[19]
	Improved replicability	[20]
	Improved reliability of delivery dates	[6]

Table A1. *Cont.*

	AM SC Context	Authors
Flexibility	Improved management of demand swings; Manufacturing volume and product flexibility; High customization, individual design	[8,14,15,22,62,67,69,72,76,79,80,95,96,101,113]
Security	Increased risk e.g., for knowledge leak	[66,87,102]
	Reduced dependency on component suppliers	[6,13]
	Improved product safety; Reduced risk for infection	[19,64]
	Reduced risk for law suits	[96]
Sustainability	Reduced (carbon) footprint, energy, emissions, pollution, waste, materials	[20,64,66,67,75,79,84,101]
	Extended lifecycle of assets	[66]
	Social: labor shift when manufacturing near consumption	[88]
Innovation	Improved design, highly complex, highly customized, integrated functions	[15,20,61,62,67,75,81,88]
	Enables co-creation	[17,19,57,60,66,73,76,94,101,102]
	Encourages innovation; Incremental product improvement/introduce new technologies to products in use	[22,88]

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