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Holistic evaluation of the impacts of additive manufacturing on sustainability, distribution costs, and time in global supply chains

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Abstract

Additive manufacturing (AM) is associated with potentially strong stimuli for revenues and cost savings, as well as reducing impacts on ecological sustainability. Nevertheless, the decision between local manufacturing with AM in the target market versus global distribution of goods requires a holistic analysis. Until now, research has merely assessed selected aspects. Comprehensive information considering ecological impacts, distribution costs, and time is limited. This paper develops a decision model assessing the impacts of AM on greenhouse gas emissions, distribution costs, and lead time in global supply chains, including a case study validating the framework.

Keywords: additive manufacturing; additive fabrication; AM; 3D printing; network planning; supply chain; logistics; production; distribution; sustainability; ecological impacts; carbon-dioxide emissions; CO2 emissions; costs; lead time

1. Introduction

Fast-moving markets require a rethinking of manufacturing methods. On the one hand, customers demand innovative, individually customized, high-quality products at a competitive price. On the other hand, companies face the challenge of shorter lifecycles, resulting in less time for amortization of investments in machinery and tooling. Additive manufacturing (AM), which is synonymous with the term three-dimensional (3D) printing, provides a solution to the challenges outlined above (Lindemann et al. 2012; Mellor et al. 2014; Rehnberg and Ponte 2018). Like digital books and music downloads, AM has been characterized as disruptive technology, allowing companies to profitably serve small market segments with customer-tailored products while operating with few or no change-over costs and finished goods inventory (Schulz et al. 2018). This facilitates mass customization or producing goods to

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meet individual customer's needs with near mass production efficiency (Berman 2012; Mohr and Khan 2015). AM enables small quantities of customized goods to be manufactured at relatively low costs by utilizing an AM process whereby products are built on a layer-by-layer basis through a series of cross-sectional slices based on digital 3D data stemming, for example, from computer-aided design (CAD) files or 3D scans (Berman 2012). The most frequently cited characteristics of AM with respect to supply chain management are simpler supply chains characterized by decentralization of manufacturing, short lead-times and low inventories, resource efficiency, waste reduction, functional optimization of the product, the possibility of quick design changes and design customization, no requirements for tooling, and the economic production of customized small batches (mass customization) ((Holmström et al. 2010; Mohr and Khan 2015; Bogers et al. 2016; Ford and Despeisse 2016).

Although today the use of AM is widespread in companies due to the economic advantages, they often do not have a well-defined understanding of how AM fits into their sustainability strategies. Therefore, this field still offers great potential for both research activities and practical improvements. Shifting from a solely cost-focused approach to an integrated and coordinated approach, AM can improve the competitiveness of the whole company and the achievement of sustainability targets (Gebler et al. 2014). The decision between local manufacturing with AM in the target market versus global distribution of goods especially requires a holistic analysis. Furthermore, the research literature provides no comprehensive model for planning a supply chain that takes into consideration ecological sustainability, distribution costs, and lead times. Until now, researchers have merely assessed case study-related data and selected aspects. This paper provides a literature overview and develops a decision model for evaluating alternative scenarios of a distribution network design, assessing the impacts of AM on greenhouse gas emissions, distribution costs, and lead time in global supply chains. Supply chains are networks formed by nodes (supply chain members) and links (connections between the members) (Carter et al. 2015). A case study is provided to validate the framework. One key aspect of the paper is its evaluation of the impacts of AM, performed by drawing on related life-cycle assessments and logistics analysis.

The first objective of this paper is to concisely explain the main impacts of AM on ecological sustainability in a global supply chain. Considering the current discussions in the literature concerning integrating AM into serial production of existing value-creation systems, providing a model supporting practitioners in decision-making is relevant. The second aim is to shed light on the environmental and economic advantages of a shift from international or onshore conventional manufacturing to AM in order to assist companies in planning their distribution structures, including considerations of the desired service level. The following research questions (RQ) derived from these underlying objectives are to be examined:

- RQ1: How can the economic and ecological impacts of different scenarios be quantified in an early stage of planning a global supply chain in a holistic decision model?
- RQ2: What are the main impacts of AM on ecological sustainability over the different life-cycle stages of an AM-fabricated product?

The next section spells out the research approach and provides an overview of the state of the research. In this way, the authors document their literature review process and particularly point out the research gap to be closed by this study. The modeling process is then described. After presenting the model itself, it is validated by an illustrative case study. The final conclusions summarize the findings of the study, presenting an approach to shape the path of a decentralized production in a more sustainable way.

2. Research background

2.1. Literature review

The current state of research in the topic of study must be identified in order to sharpen the research agenda. An extensive literature review supports the identification of the research question of this article. Many scientific texts do not thoroughly document the process of literature review. However, research is a collaborative endeavor since each researcher builds on what has been worked out before (Vom Brocke et al. 2009). The process of searching the literature must therefore be comprehensibly described. Only then readers are able to assess the exhaustiveness of the review and judge the suitability of potential (re)use of the results. The literature review highlights the sources relevant to the topic and thus makes a crucial contribution to the relevance and rigor of research. Relevance is enhanced by avoiding the repeated analysis of what is already known (Baker 2000), and rigor is derived from an effective use of the existing knowledge base (Hevner et al. 2004). The term “rigor” characterizes the reliability and validity of the search process. As such, validity describes the degree to which the literature search accurately reveals the sources used by the reviewer, i.e., the selection of databases, publications, and keywords, and the articles covered. Reliability, in turn, describes the replicability of the search process. For the literature review, the authors followed the framework proposed by Vom Brocke et al. (2009) as presented in Figure 1. Phase I of the five phases defines the scope of the review. In this case, the scope includes state-of-the-art of evaluation models regarding the impacts of AM on sustainability, distribution costs, and lead time in global supply chains. The literature review serves the purpose of gaining new and synthesizing existing research outcomes. Furthermore, research methodologies commonly used in this field are identified.

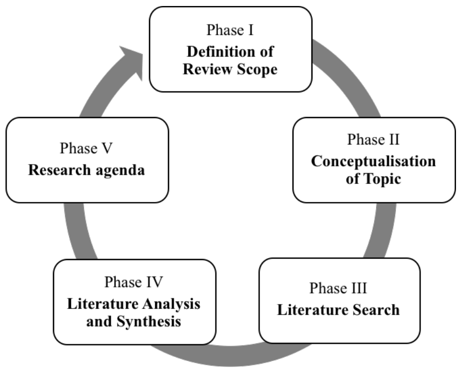

Fig. 1. Framework of the literature review (following Vom Brocke et al. (2009)).

To clearly define the scope of the review, the authors draw on the established taxonomy for literature reviews as presented by Cooper (1988), highlighting relevant categories in Figure 2. The focus (1) of a literature review is concerned with what is of utmost importance to the reviewer. In this case, the authors focus on the research outcomes described or applied in the article analyzed. The main goal (2) of this literature review is to summarize and integrate findings. The organization (3) of the review can be characterized as conceptual, because works relating to the same abstract ideas appear together. With regards to the characteristic of the perspective (4), the viewpoint of the reviewers played an active role in the editorial process. The reviewers undertook the task of accumulating and synthesizing the literature in order to demonstrate the value of their point of view concerning how the holistic evaluation model should be defined. The audience distinction (5) manifests itself through the reviewers’ writing style. Since the intention is to address specialized scholars as well as practitioners in companies, the authors do not strictly follow a scientific writing style. The degree of coverage of sources (6) is characterized as exhaustive and selective.

	CHARACTERISTIC	CATEGORIES			
1	FOCUS	**Research Outcomes**	Research Methods	Theories	**Applications**
2	GOAL	**Integration**	Criticism	Central Issues	
3	ORGANISATION	Historic	**Conceptual**	Methodological	
4	PERSPECTIVE	Neutral Representation	**Espousal of Position**		
5	AUDIENCE	**Specialised Scholars**	**General Scholars**	**Practitioners / Politicians**	General Public
6	COVERAGE	Exhaustive	**Exhaustive and Selective**	Representative	Central / Pivotal

Fig. 2. Taxonomy of literature review (following Cooper (1988)).

Phase II of the literature review involves the conceptualization of the topic. After identifying key concepts of the subject by consulting seminal textbooks, working definitions of key terms were provided. The search process in Phase III encompassed keyword, backward, and forward searches, as well as an ongoing evaluation of sources. Documentation of the search process is crucial, both to ensure the replicability of the literature search and to enable other scholars to evaluate whether the reviewers sufficiently matched the topic under investigation. For the English and German keywords and synonyms used in the search process, see Figure 3.

List of Keywords

Keyword 1	
3D Printing	3D Druck
Additive Manufacturing	Additive Fertigung

AND

Keyword 2	
Logistics	Logistik
International Logistics	Internationale Logistik
Global Logistics	Globale Logistik
Supply Chain	Lieferkette
International Supply Chain	Internationale Lieferkette
International Value Chain	Internationale Wertschöpfungskette
Global Supply Chain	Globale Lieferketten
Global Value Chain	Globale Wertschöpfungskette
Logistics Costs	Logistikkosten
Supply Chain Costs	Supply-Chain-Kosten
Transport Costs	Transportkosten
Distribution Costs	Distributionskosten
Order Fulfillment	Auftragsabwicklung
Sustainability	Nachhaltigkeit
Ecological Impacts	Ökologische Auswirkungen
Emission	Emission
Carbon Dioxide	Kohlenstoffdioxid
CO2	CO2
Carbonic Acid	Kohlendioxid

Fig. 3. Keywords for the literature search.

The number of articles identified by keyword search had to be limited to only those articles relevant to the topic at hand. The evaluation of the article titles and abstracts reduced the number of articles from 6,710 to a relevant sample of 49 articles from selected databases (see Figure 4). The focus was on articles published in scholarly journals and proceedings of conferences, since these have typically been peer-reviewed before publication.

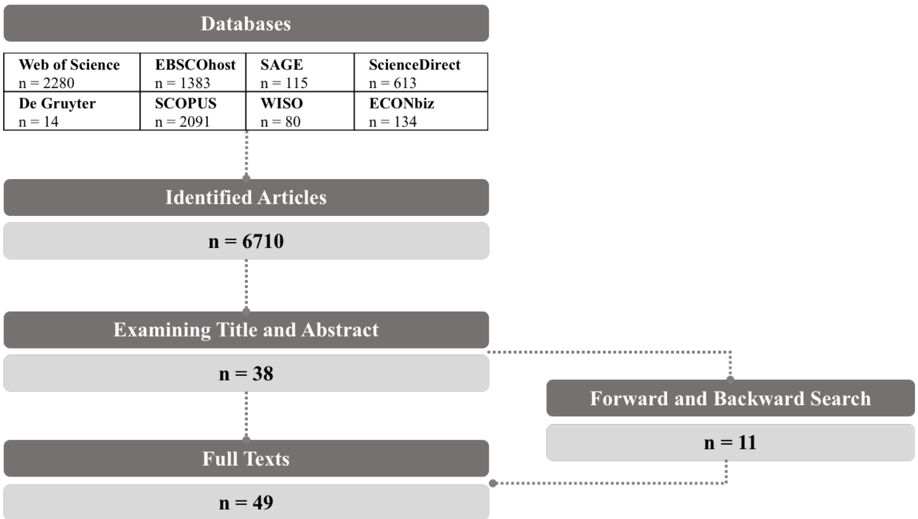

Fig. 4. Databases and statistics from the literature search process.

After having collected sufficient literature on the topic, it was analyzed and synthesized in Phase IV of the literature review. The concept matrix presented in Figure 5, which subdivides topic-related concepts into different units of analysis, was used for the analysis.

Source	Ecological Impact		Supply Chain Impact			
	Sustainability	Greenhouse Gas Emissions	Distribution Costs	Network Structure	Lead Time	Process
(Angeleanu 2015)	X					X
(Barz et al. 2016a)	X			X		X
(Barz et al. 2016b)	X			X		X
(Bogers et al. 2016)				X		X
(Boon and van Wee 2017)	X		X	X	X	
(Cerdas et al. 2017)	X			X		
(Chen 2016)			X	X	X	
(Chen 2017)	X			X		
(Durach et al. 2016)			X	X	X	X
(Faludi et al. 2015)	X					X
(Feldmann and Pumpe 2016)			X		X	X
(Fera et al. 2016)						X
(Flores Ituarte et al. 2016)				X		X
(Ford and Despeisse 2016)	X			X		
(Garg and Lam 2015)	X		X	X		
(Gebler et al. 2014)	X	X		X		X
(Hasan et al. 2013)						X
(Hashemi et al. 2014)	X		X		X	X
(Hofmann and Oettmeier 2016)	X					X
(Hopkinson et al. 2006)	X					X
(Huang et al. 2013)	X	X	X	X	X	
(Janssen et al. 2014)	X					X
(Joshi and Sheikh 2015)	X					X
(Kellens et al. 2017)	X					
(Kieviet and Alexander 2015)			X		X	
(Kothman and Faber 2016)	X			X		
(Laplume et al. 2016)				X		X
(Le Bourhis et al. 2013)	X					
(Lin et al. 2014)			X	X	X	
(Mani et al. 2014)	X					
(Mellor et al. 2014)	X					
(Manners-Bell and Lyon 2012)	X			X		
(Mohr and Khan 2015)	X		X	X	X	X
(Oettmeier and Hofmann 2016)				X		X
(Park and Jun 2017)	X					
(Petrick and Simpson 2013)	X					X
(Petschow et al. 2014)	X	X	X	X		X
(Pour et al. 2016)	X		X	X	X	X
(Reeves 2018)	X					
(Rehnberg and Ponte 2018)			X	X	X	X
(Rogers et al. 2017)					X	X
(Ryan et al. 2017)				X		X
(Silva and Rezende 2013)	X		X	X		X
(Steenhuis and Pretorius 2016)	X					
(Tang et al. 2016)	X			X		
(Thomas 2016)	X		X			X
(Travers 2015)		X		X		X
(Wigan 2014)	X			X		X
(Woodcock 2011)		X				X

Fig. 5. Concept matrix.

The synthesis of the literature resulted in the research agenda (Phase V), comprising the research questions for this article (cf. Webster and Watson (2002)). Certain subject areas or fields of the matrix are underrepresented in current research, which highlights research areas that provide a high potential for insightful questions. A detailed overview of the relevant state of the research areas is provided in the following section.

2.2. State of the field and research gap

AM is a theoretical and applied research area that is increasingly receiving attention in the literature. According to the research objective, an understanding of its drivers will help to compare the distribution costs, lead time, and ecological impacts of AM with those of non-AM methods. Figure 5 provides an overview of the main publications structured around major conceptual elements. Research is limited to case studies and general-level analysis (Pour et al. 2016). The present studies are characterized by a wide heterogeneity in terms of the applied analyses, the empirical data base (lacking in many cases), and the presentation of the results, which means that the findings are not strictly comparable (Boon and van Wee 2017). Few studies have quantified the environmental and economic implications of AM parts and supply chains (Huang et al. 2013; Thomas 2016), while many studies focus on the material and energy consumption of AM processes (Baumers et al. 2010; Barz et al. 2016b; Kellens et al. 2017). Only two quantitative studies considered lead time implications in the supply chain (Huang et al. 2013; Chen 2016). In many cases, the publications are limited to specific AM technologies or a particular industry (Hashemi et al. 2014; Garg and Lam 2015; Joshi and Sheikh 2015; Kothman and Faber 2016; Zhao et al. 2016). Some findings are documented in the form of single (individual) case studies, which due to their limited sample scope do not allow for a valid universal induction (Petschow et al. 2014; Burkhart and Aurich 2015; Kothman and Faber 2016). Others compare AM to a specific conventional manufacturing method, such as injection molding (Huang et al. 2013). There is no comprehensive, generalizable decision model in the literature covering distribution costs, lead time, and greenhouse gas emissions. In many cases, the reason for this is that the underlying parameters are only limitedly stated, or that the analysis is restricted to a single supply chain process or individual cost element. In addition, the constructs and their indicators are often not sufficiently validated. However, these are essential for determining cause-effect relationships in a scientifically accurate manner. Also, recommendations for action are only justified by plausibility considerations, and no valid calculations are provided for relevant influencing factors. This deficit supported the choice of this study's objectives and approach.

2.3. Conclusions

The issues can be summarized as follows: there is no holistic, quantitative model available for evaluating alternative design scenarios for a global supply chain that considers the impact on distribution costs, lead time, and the environment. Existing quantitative models are designed for specific case studies. It is therefore difficult for practitioners to understand on a quantitative level how investments in AM contribute to improvements in distribution costs, lead time, and greenhouse gas emissions. The first objective of this paper is therefore to concisely explain the main economic and ecological impacts of AM in a global supply chain. The second aim is to assist companies in planning their distribution structures, including considerations of the desired service level. Therefore, the paper develops a decision model facilitating the selection of a suitable distribution structure. The next section provides information on AM and its economic and ecological impacts.

3. Additive manufacturing impacts on global supply chains

What follows is an overview of the major impacts of utilizing AM in a global supply chain. First of all, cost impacts are analyzed (3.1); secondly, AM impacts on distribution time and service level are explained (3.2); and thirdly, the authors provide an overview of AM effects on ecological sustainability (3.3).

3.1. Additive manufacturing impacts on costs

To identify the operational costs associated with implementing AM per process area in the supply chain, the authors mainly build on the findings presented by (Feldmann and Pumpe 2016). First of all, cost drivers per process of the Supply-chain operations reference (SCOR) model (Supply Chain Council Inc 2012) were identified. A cost driver is any factor that causes a change in the cost of an activity, reflecting any linkages or interrelationships that affect it. Prior to identifying cause-effect relationships, all relevant supply chain processes were investigated and modeled. Secondly, using scenario analysis, the direction of influence was determined per cost driver (increase versus decrease of the reference parameter). For example, the number of raw material orders tends to decrease when sourcing a limited number of raw materials for AM (e.g., plastic granulates supplied in large bags) from a limited number of suppliers (instead of sourcing a larger variety of individual components from different suppliers, which is necessary without AM). Thirdly, applying the criterion magnitude of cost impact prioritizes cost drivers. Finally, the direction and extent of the impact on costs was determined (e.g., a decrease of personnel costs associated with processing purchase orders). The following sections provide a decomposition of each of the supply chain processes: source, make, deliver, and return (for details, cf. Feldmann and Pumpe (2016)). Differing from the structure of the SCOR model, the area “plan” is subsumed under the according process areas to increase rigidity and comprehensibility.

SOURCE: The sourcing process encompasses the ordering or scheduling of deliveries and receipt of goods and services. It includes issuing purchase orders; scheduling deliveries; receiving, validating, and storing goods; and accepting the invoice from the supplier (Supply Chain Council Inc 2012). Overall, sourcing costs appear to decrease in an AM scenario. The sub-process “schedule product deliveries” was accredited as the major cost impact. Planning reliability – in particular, accuracy of demand forecasts and prediction accuracy with regards to the life cycle of a product respectively the associated materials to be sourced – tends to increase significantly. Instead of planning and forecasting a larger variety of different materials (e.g., different variants of plastic components), only a limited set of raw materials must be planned for (e.g., a small variety of granulates), resulting in less planning effort. Furthermore, the number of suppliers to be dealt with decreases, resulting in lower administrative personnel costs. Forecast accuracy for the generic AM materials (e.g., big bags of generic plastic granulate) increases (“law of large numbers”), thus reducing both inventory costs (handling, capital costs, infrastructure) and out-of-stock costs. The decline of out-of-stock costs is mainly caused by fewer additional fees for expediting inbound shipments in order to meet the production schedule and prevent line stops or penalties. The empirical study also identified a reduction in inbound transportation costs. Expensive airfreight is replaced by less expensive modes of transportation such as rail, road, or water due to a reduced need for expediting unplanned inbound shipments. The reduced need for expedited shipments is also based on higher flexibility in production. Scrapping costs for materials of products being phased out (end-of-life) are cut since there is no need to carry large inventories of specific components when manufactured on demand. Moreover, supplier tooling costs (e.g., for casting molds) decrease due to a reduction in both acquisition costs, resulting in depreciation costs, and scrapping costs at end-of-life. Additionally, costs associated with the country of origin can potentially drop. For instance, import duties decrease by sourcing digital data for AM instead of physical goods. Additionally, trade barriers can be evaded without setting up a plant or a local supplier base in the sales region.

MAKE: The making process includes the activities associated with the conversion of materials or the creation of the content for services, also referred to as production or manufacturing. The target of this process is to add value to products through mixing, separating, forming, machining, and chemical processes (Supply Chain Council Inc 2012). To summarize, make costs appear to decrease in an AM scenario (Feldmann and Pumpe 2016). The findings of the case studies from the companies indicate that implementing AM mainly results in a decrease in direct labor costs, tooling costs, annual depreciations, scrap value, and waste disposal costs. Cost effects for these drivers depend heavily on the AM technology, the AM machine brand, the AM materials used, and the geometry of the product itself. Material costs per piece are determined by both price and quantity of material per piece. Since both cost drivers depend heavily on the quality requirements, the AM technology, and the material chosen, no general statement can be made concerning the derivable cost effect. The quantity required per piece appears to decrease for many products. This is first of all due to the nature of AM, since only the material quantity that is needed is used to form the shape or geometry layer-by-layer (apart from support materials), thus consuming less material than subtractive manufacturing methods such as turning. Furthermore, AM products designed with a honeycomb interior structure use less material than comparable products manufactured using conventional methods such as casting or milling that result in a solid structure. On the contrary, the need for AM-specific auxiliary materials (e.g., support materials such as brims and corrosives for surface treatment) increases material costs. Labor costs drop as the number of assembly steps (time) decreases, since parts to be put together via assembly steps in a conventional manufacturing scenario can be produced in one step. However, these labor cost savings may be (over)compensated in the case of the need for new processes such as surface treatment. The number of change-overs (respectively the time needed), i.e., converting a machine from producing one product to another, and associated costs decreases due to the omission of retooling. The lack of specific tools such as molds per product variant results in a significant reduction of depreciations for tooling assets. The same applies to the amount of conventional machinery (e.g. for milling, drilling) required to manufacture a geometry, compared to one AM machine meeting the same requirements. AM-specific pre-processing steps, however, such as heating an extruder or a platform, can result in compensating cost effects with respect to labor and energy. Moreover, there is a compensating effect resulting from the potential increase of post-processing costs caused by finishing activities after the parts have been manufactured in order to ensure conformance to defined specifications, such as the removal of support materials (e.g., rafts, skirts, and brims) and surface treatment (e.g., deburring, sanding, or priming). There are also contradictory effects with respect to waste disposal costs. On the one hand, due to the character of AM, there is less waste to be disposed of as compared to that created by subtractive manufacturing (controlled material removal or machining). On the other hand, the support materials, as well as a variety of chemical and sealant materials (e.g., for cleaning or smoothing the finished surface), must be disposed of. This might also include the storage and handling of hazardous materials such as acetone used for ABS surface treatment, resulting in additional inventory and processing costs. One offsetting effect is the higher level of reusability of the raw materials, especially when additively manufacturing plastic components.

DELIVER: The delivery process includes all activities associated with the creation, maintenance, and fulfillment of customer orders, including receiving, validating, and creating customer orders; scheduling order deliveries; picking, packing, and shipping orders; and invoicing customers (Supply Chain Council Inc 2012). Deploying AM to decentralized distribution centers in the sales region, as opposed to using conventional manufacturing methods in one central plant, can significantly reduce freight costs. There are less expedited shipments at higher freight rates (e.g., overnight express) are necessary to meet requested delivery dates due to higher flexibility and lower change-over costs. Other out-of-stock costs such as lost sales, lost customers, and penalties decrease for these same reasons. Moreover, the weight of AM products tends to decrease due to the frequent use of honeycomb rather than solid structures, resulting in lower freight rates. There is also potential for decreases in customs duties and the removal of trade barriers. In some countries, a minimum level of local content is required under trade laws when determining trade tariffs allowing the import of goods or giving foreign companies the right to manufacture in a particular place. Local AM has the potential to reduce customs duties by obtaining favorable tariffs with locally manufactured product parts containing sufficient local content. AM in the sales region may be less expensive than competing alternatives such as setting up a plant in the sales region, utilizing a local supplier base, or a complete knock down (CKD). Enhancing the portion of local content without setting up a plant in the sales region allows for lower prices. Moreover, other trade barriers based on the country of origin can be overcome, enabling companies to enter new regional markets. Apart from tariffs and export control regulations, the country of origin also has an effect on marketing, utilizing the public image of the country (Friederes 2006). Manufacturing on demand using AM decreases inventory costs – namely capital charges, handling costs, and scrapping costs – for finished goods. Rationales include the higher flexibility of AM and the omission of campaign-based production, inflating stock levels in conventional manufacturing due to changeover costs. The higher the number of distribution echelons in the supply chain, the higher the diminishing effect on inventories due to a reduced need for safety stocks per echelon. Deploying AM to decentralized distribution centers in the sales region, rather than utilizing conventional manufacturing methods in central plants, can significantly reduce inventory costs by removing safety stocks.

RETURN: The return process involves the activities associated with the reverse flow of goods. It encompasses the identification of the need to return, the disposition decision-making, the scheduling and shipment of the return, and the receipt of the returned goods (Supply Chain Council Inc 2012). The authors deviate from the SCOR model by subsuming repair, recycling, refurbishment, and remanufacturing processes into the return process. Two cost drivers appear to be relevant; the first is that the portion of replacement deliveries (swap) increases compared with the portion of repairs, since the level of accessibility of the product decreases because even complex geometries can be manufactured without mechanical interfaces (e.g., fittings in conventional assembly). As a result, costs increase both for the analysis to decide between repairing and swapping and for disassembling the product for repair. Secondly, the level of sorting accuracy for waste disposal is lower, especially for products manufactured as hybrids, which combine heterogeneous materials by melting. Both of these drivers result in rising costs.

3.2. Additive manufacturing impacts on distribution time and service level

The competitiveness of the logistics service level, which is determined by delivery reliability, lead times, and flexibility, is enhanced by utilizing AM, thereby impacting the sales volume positively (Feldmann and Pumpe 2016). Delivery reliability, defined as adherence to planned delivery dates (punctuality), can be achieved by short processing times with low fluctuations (Nyhuis and Wiendahl 2003; Chopra and Meindl 2016). Lead times are determined by inventory levels and by lead times in sourcing, producing, and delivering (Schönsleben 2007; Chopra and Meindl 2016). Flexibility is the ability to successfully manage changes and uncertainties regarding customer requirements and own capacities (Schönsleben 2007). High flexibility can be achieved by qualitatively adaptable and quantitatively scalable capacities and processes (Schnetzler et al. 2007). In an AM scenario, the logistics service level is higher due to the increased availability of products determined by smaller economic lot sizes and higher flexibility in production, thus potentially outperforming competitors. When running AM production in the sales region instead of in a central "world factory," the reduced distance to the end customer can significantly diminish lead times.

3.3. Additive manufacturing impacts on ecological sustainability

A review of the literature reveals numerous definitions of sustainability that take different objectives into account. The most frequently quoted definition comes from the UN World Commission on Environment and Development (WECD), which defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development. 1987). In keeping with this definition, the authors understand sustainability as operating practices of a value-creation system that meet the needs of present users with respect to costs and service level without compromising the ability of future generations to meet their own needs, particularly with regard to scarce natural resources. Sustainable operating practices support ecological, human, and economic health and endurance. Sustainability presumes that resources are finite and should be used conservatively and wisely with a view to long-term priorities and consequences of resource use. Although the identified literature addresses the relationship between AM and sustainability (Figure 5), there is no comprehensive and structured overview of the ecological impacts of facilitating AM in a value-creation system. In order to close this research gap, the authors developed the life cycle model of an AM-fabricated object to systematize its ecological impacts (Figure 6). The life cycle of an object is defined as a progression through a series of differing stages over a lifespan. For a component or finished product being fabricated by an AM machine, its life cycle progresses through the following stages: (1) sourcing, (2) manufacturing, (3), distribution, (4) customer use, (5) maintenance or repair, and (6) disposal at end-of-life. Following this sequential progression, Figure 6 provides an in-depth decomposition of each of these six life cycle stages' impacts on ecological sustainability. To identify relevant impacts of AM on ecological sustainability, activities per stage were detailed on the basis of drivers and scenario analysis to identify cause-effect relationships, analogous to the approach for identifying the cost impacts (Section 3.1).

Most sourcing activities (Stage 1) were considered insignificant regarding their impact on sustainability in an AM scenario. Overall, AM sourcing appears to be more environmentally sustainable than a conventional manufacturing setup (see Figure 6). The level of impact on sustainability, however, depends heavily on the geometry of the object, the raw materials, and the AM technology used. The manufacturing (Stage 2) of the AM objects' life cycle includes the activities associated with the conversion of materials or creation of the content for services, also referred to as production or manufacturing (Supply Chain Council Inc 2012). When validating the sustainability drivers by utilizing the generic SCOR process model, the sub-processes "produce," "post-processing," and "waste disposal" were identified as main drivers impacting ecological sustainability. To summarize, impacts on ecological sustainability in the manufacturing stage are manifold; of particular importance is the fact that less material is used as compared to non-AM methods. There are, however, numerous compensatory effects having a negative impact on sustainability that must be taken into account, such as additional waste due to post-processing activities.

Life cycle of an AM fabricated object: ecological impacts						
	(1) Sourcing	**(2) Manufacturing**	**(3) Distribution**	**(4) Customer Use**	**(5)Maintenance , Repair**	**(6) Disposal at End-of-Life**
Advantages	• Less fuel consumption and emissions due to – lower number of inbound shipments (Petschow et al. 2014; Cerdas et al. 2017) – expedited emission-intense airfreight replaced by less intense modes of transportation (Boon and van Wee 2017) – higher degree of reusable residuals out of the manufacturing process (Pour et al. 2016) • Lower number of SKU and lower inventory levels, e. g. by substituting the movement of physical goods by sending or storing digital files (Burkhart and Aurich 2015; Mohr and Khan 2015; Ford and Despeisse 2016) • Less scrapping of obsolete raw material inventories (Mohr and Khan 2015)	• Less material used, in particular in cases of cavities and honeycomb structures (Hopkinson et al. 2006; Mohr and Khan 2015; Pour et al. 2016; Reeves 2018) • No respectivey less waste of raw materials, especially due to reuse of, e.g., support materials (Hopkinson et al. 2006; Petrovic et al. 2011; Bühner 2013; Lipson and Kurman 2013; Gebler et al. 2014; Janssen et al. 2014; Wigan 2014; Reeves 2018) • Energy costs are reduced, e.g., due to omitting diverse machines or internal transportation between different production steps (Woodcock 2011; Huang et al. 2013; Reeves 2018) • Reduced need for tooling (Petrovic et al. 2011) • No use of adjuvants such as coolants, lubricants, or other environmentally harmful substances (Gebler et al. 2014; Petschow et al. 2014; Oettmeier and Hofmann 2016) • Less scrapping of obsolete inventories (semi-finished goods)	• Less fuel consumption and lower emissions due to – shorter to no transport distance to point-of-use or point-of-consumption (Garg and Lam 2015); (Manners-Bell and Lyon 2012; Petrick and Simpson 2013; Nyman and Sarlin 2014; Pour et al. 2016) – less weight in cases of lightweight construction, e.g., cavities and honeycomb structures (Petschow et al. 2014) – expedited emission-intense airfreight shifts to less intense modes of transportation like rail, road, or water • lower inventory levels due to print-on-demand, postponement, and lower number of echelons in chain (Burkhart and Aurich 2015; Mohr and Khan 2015; Boon and van Wee 2017) • less scrapping of obsolete inventories (finished goods) (Ford and Despeisse 2016)	• Lightweight construction results in less fuel consumption and lower emissions, e.g., if objects are used in automotive or aeronautic branches (Gebler et al. 2014); (Huang et al. 2013); (Petschow et al. 2014)	• Inexpensive manufacturing of spare parts not available without AM (Woodcock 2011) • Restoring the original geometry of a worn or defective part (Petschow et al. 2014)	• Less waste to be disposed of and less material to be recycled in case of lightweight constructions (cavities and honeycomb structures) (Gebler et al. 2014)
Disadvantages	• Higher frequency of small transports might compensate for the transportation savings above (in the case of many decentralalized AM machines instead of one central manufacturing facility) (Boon and van Wee 2017)	• Higher energy consumption per piece (as a tendency) (Huang et al. 2013) • Additional waste due to post-processing, e.g., for surface treatment and removing support materials (Petschow et al. 2014) • Decentralized manufacturing by many laymen increases risk of faulty objects being disposed of (Petschow et al. 2014; Pour et al. 2016) • Emission of nano particles while manufacturing (Cerdas et al. 2017)	• Higher frequency of small transports might compensate for the transportation savings above (in the case of many decentralized AM machines instead of one central manufacturing facility)	• Consuming more products and resulting resources than really needed due to simple, decentralized fabrication, e.g., by private end customers (rebound effect, “throw-away culture”) (Petschow et al. 2014)	• Portion of replacement deliveries (swaps) increases compared to the portion of repairs due to limited accessability (Feldmann and Pumpe 2016)	• Recyclability of some raw materials unknown (Bourell et al. 2009) • Unmixed disposal recyclability of two or more materials amalgamated in one manufactured object is difficult (Ford and Despeisse 2016)

Fig. 6. Life cycle of an AM fabricated object: ecological impacts.

Distribution (Stage 3) comprehends the logistics activities associated with the creation, maintenance, and fulfillment of customer orders (Supply Chain Council Inc 2012). When analyzing the impacts on ecological sustainability, the sub-processes of the SCOR model “process warehouse activities” and “ship product” were accredited with the main effect on the environment. There is a potentially compensating effect working in opposition to the opportunities mentioned in Figure 6: the emissions caused by a higher frequency of small shipments from many decentralized AM machines instead of one central manufacturing facility. This especially applies to future visions of “desktop factories” for private use. During customer use (Stage 4), ecological impact unfolds primarily in the case of lightweight construction (cavities and honeycomb structures) of the AM-fabricated objects, resulting in less fuel consumption and emissions (e.g., if objects are used in the automotive or aeronautic branches). On the other hand, simple, decentralized AM fabrication can encourage the production of more goods than is actually necessary (“throw-away culture”). This so-called rebound effect occurs when an expected increase of resource efficiency is reduced by the behavior of entities or other reactions of a system (Gillingham et al. 2016).

Stage 5, maintenance and repair subsumes all activities associated with maintenance, repair, and refurbishment. The material-applying process for the maintenance or repair of worn components utilizing AM is called rapid repair (Gebhardt 2016). AM allows for the restoration of the original geometry of a worn or defective part. Moreover, AM enables longer life cycles through inexpensive manufacturing of spare parts for which there are no longer any sources of supply by facilitating re-engineering of components using 3D scanning. In contrast, two cost drivers appear to negatively impact ecological sustainability. The portion of replacement deliveries (swaps) increases compared to the portion of repairs, so the level of accessibility of the product decreases since even complex geometries can be manufactured without mechanical interfaces (e.g., fittings in conventional assembly) (Feldmann and Pumpe 2016). Stage 6, disposal, involves the activities associated with disposing of waste at the end of a product’s life cycle. These activities include collecting, processing, and recycling or disposing of the product’s waste materials in accordance with environmental guidelines or laws. In laying material only where it is needed, the amount of material being used is significantly lower, which helps to decrease the quantity of material to be disposed of. The level of sorting accuracy for waste disposal, however, is lower, especially for products manufactured as hybrids that combine heterogeneous materials by melting.

3.4. Conclusions

The preceding sections have provided an overview of the major impacts of utilizing AM in a global supply chain. First of all, cost impacts in the process areas of sourcing, making, delivering, and returning were analyzed, building on the empirical study conducted by Feldmann and Pumpe (2016). The process areas of sourcing and delivering seem to be the most promising with respect to cost reduction. For the area of making, cost effects depend heavily on the AM technology, the AM machine brand, the AM materials used, and the geometry of the product itself. Secondly, AM impacts on distribution time and service level were explained concisely (3.2). Thirdly, the authors provided a structured overview of AM’s effects on ecological sustainability, systemized according to the life cycle stages of an AM-fabricated object. Positive impacts on ecological sustainability could be identified across all six of the life cycle stages. However, also the potentially compensating effects are manifold. The following section will first specify the research methodology of the modeling process to ensure the approach’s scientific rigor. Afterwards, the model itself will be presented.

4. Modeling process

A model is a systematic description of an object or phenomenon that shares important characteristics with its real-world counterpart (Börner et al. 2012). Models are simplified representations of a system. By attempting to reduce the real world to a fundamental set of elements and laws, models support detailed investigation in order to gain insights for describing, explaining, forecasting, and designing real systems. This study was based on the modeling process proposed by Adam (1997), which has been proven in numerous application-oriented research projects. Logical and comprehensive model development was accomplished by the precise definition of five phases with specified results, as illustrated in Figure 7. The relevant features of the model elements were identified by an analysis of the symptoms of the real-world problem and a subsequent problem formulation. This is the basis for the formulation of the modeling objectives and restrictions. In the final step, the model was validated using a case study. In the present case, the symptom is a lack of understanding of how to quantify the economic and ecological impacts of different alternatives at an early stage of planning a global supply chain respectively distribution network. This is mainly a result of the lack of a comprehensive quantitative decision model to evaluate the impacts of alternative scenarios, such as a local production with AM in the target market versus global distribution of goods. The decision model is then derived based on these findings, taking into account the major factors impacting sustainability, distribution costs, and lead time. In the final stage of modeling, the model is validated in a case study to ensure practical suitability.

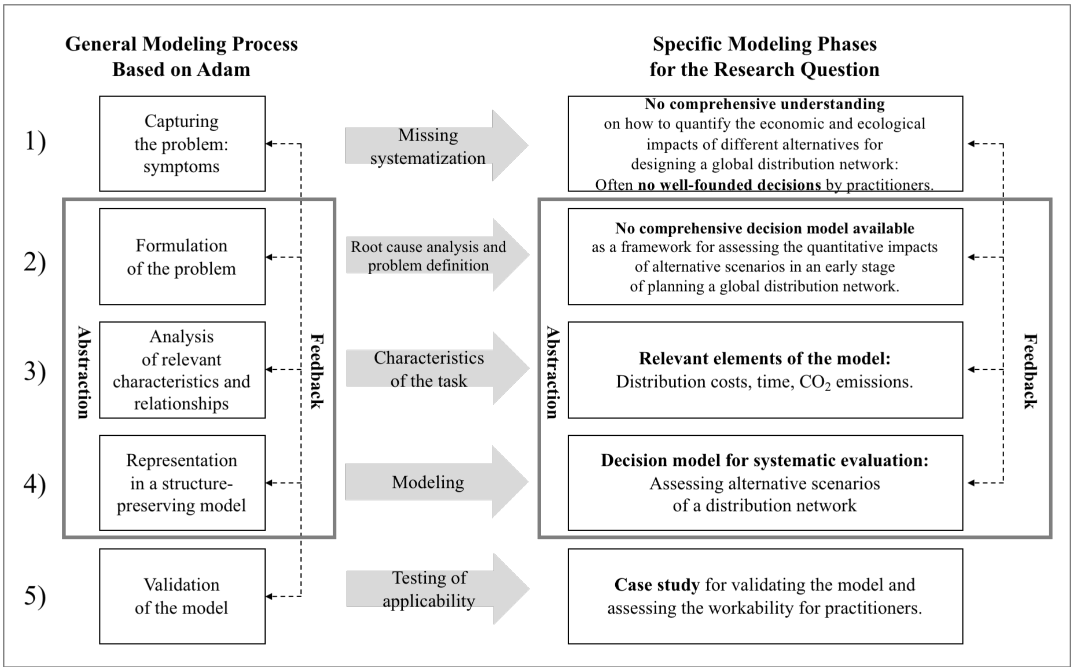

Fig. 7. Modeling process (own representation base on Adam (1997)).

In the next section, the decision model will be presented.

5. Setting up the optimal distribution strategy

The planning of distribution, considering the described target dimensions of costs, time, and emissions, requires a holistic and workable approach or framework. Cross-functional-drivers and independencies determine the overall performance of logistics systems (Chopra and Meindl 2016). Thus, no linear optimization approach or calculation methodology is developed yet to solve the described problem. As part of the value chain, distribution logistics, the interface with the customer, should be aligned with the customer's demands. Following this idea, the approach in this article evolves constantly, beginning with the delivery service strategy. As for performance indicators, the service level represents the key to or crucial value for the assessment of a supply chain. It shows the value or share of orders that are delivered within an agreed upon or planned timeframe (Gudehus 2005; Wildemann 2010; Chopra and Meindl 2016).

For the described planning problem, a top down planning approach with returns to the previous cycle, will be developed. The first step of the approach is defining the process chain based on individual company-specific ideas or on reference models (Poluha 2010; Supply Chain Council Inc 2012) After defining the process chains in a third step, the internal and external factors are examined. The internal conditions are, for example, existing logistical structures and cost restrictions that can be optimized in the planning phase. As far as external transportation or country-specific conditions are concerned, companies can only act in compliance and have to adapt to the prevailing situations

(Kummer 2010). According to the definition of the processes and the investigation of the framing conditions, companies have different alternatives to organize the supply of the target market under the restriction of the defined service level. The evaluation of the different options occurs under the examination of the different characteristics of the resources that can be adopted when setting up a distribution system (Dircksen 2012).

The following sections of this article are built up analogously to the steps of the hierarchical approach, which is displayed in Figure 8. Chapter 6 therefore examines the corporate and country-specific conditions as well as possible scenarios differentiated by order processing, transportation, storage, and AM. Following the idea of the procedure model presented in this chapter, validation should be performed after modeling a problem. An extensive and appropriate case study of a supply chain from Brazil to Germany is therefore presented in Chapter 7.

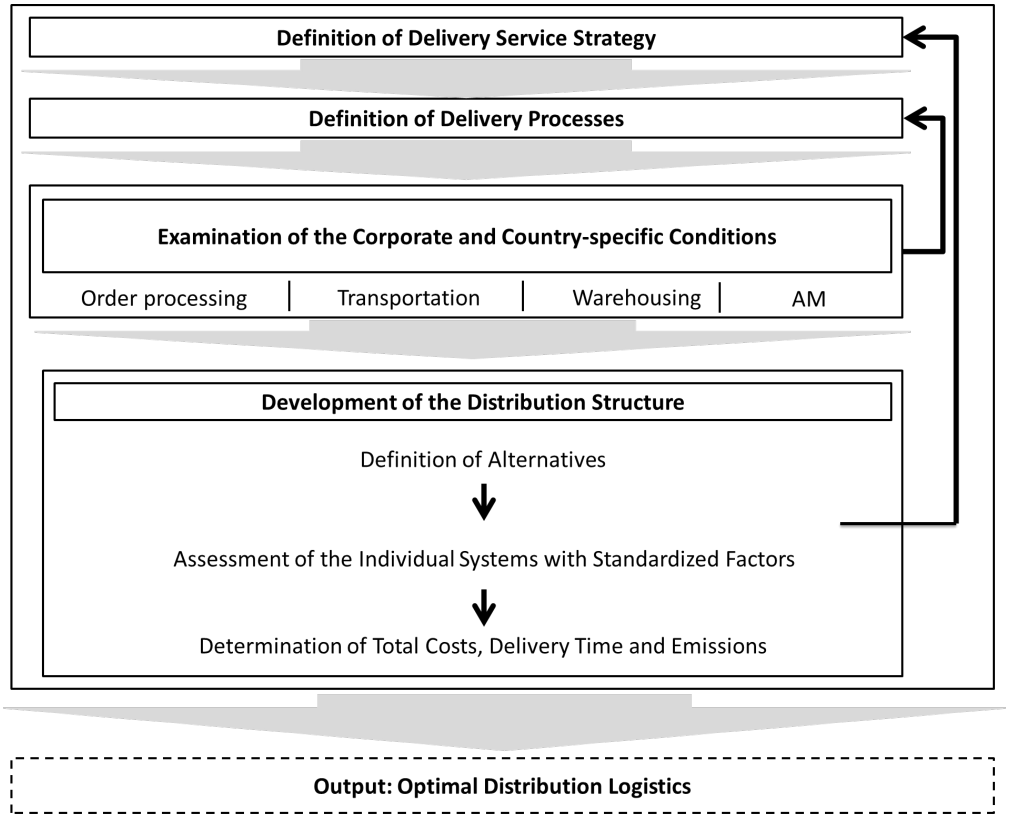

Fig. 8. Procedural model for the setup of the optimal distribution strategy (Dircksen 2012).

6. Corporate and country-specific conditions and definition of criteria for decisions

6.1. Order processing

On the one hand, processing is concerned with company-internal processes, and on the other hand, it interacts with external actors. As borders are crossed, companies have to operate with customs authorities. Also, the different treatment regarding the valuation basis for customs and taxes due to the redesign of the supply chain by the implementation of AM has not been conclusively, legally clarified (Travers 2015). However, the import regulations and processes in the target country play a decisive role which affects expenditures as well as lead times (Organisation for Economic Co-operation and Development 2003; Lewis 2009). Due to these underlying conditions, customs represent a significant part and must be integrated into the model approach.

6.2. Transportation

Depending on the respective processes and distribution structures, the evaluation of transportation options must be completed in advance as part of the planning process. Since a direct comparable abstraction of specific variables cannot be achieved, detailed knowledge of the conditions, prices, and terms are indispensable for the planning and evaluation of the respective transportation options (Klatt 1997; Wildemann 2010; Pfohl 2018).

When transportation weights are measured, ocean shipping is the most significant carrier with a share of 80% of the international goods transported. The advantage of ocean transportation lies mainly in the vast quantity of goods that can be transported over great distances (Kummer 2010; Crabtree et al. 2017). The internationally significant operating mode of liner shipping is mainly deployed in container traffic. The providers of line shipping services face an anonymous transportation market on the demand side (Böhme 1997).

Along with ocean shipping, airfreight makes up more than one third of the transported volume based on the value of the goods; however, this still accounts for only 1% of the worldwide movements of goods (Crabtree et al. 2017). Overall, "freight-only" aircraft is used as a means of transportation to a much lesser degree since the joint transportation of passengers and freight offers the advantage of more flight routes (International Air Transport Association - IATA (Montreal, Canada) 2018).

For rail transportation, trends show that the use of carriers in modern logistical concepts is restricted to regular block trains between huge industrial centers. In the international context, the complexity increases noticeably due to technical specifications and heterogeneous regulations (Kummer 2010).

There are only a few states where road transportation is not the dominant mode of inland transportation. The supply side of transportation services can be described as "atomized" in most countries, since it is dominated by a large number of small and medium-sized enterprises. Aside from vehicles and the various actors, road freight transportation requires, on the infrastructural level, roads and transshipment facilities (Aberle 2009).

Regarding the decision variables – costs, time and CO_2 emissions – the configuration options for transportation, (e.g., the mode of transportation, the routing, and the distance of the individual transportation legs) lead to an extensive planning procedure. In many cases, those complex transportation structures avoid a detailed, forward-looking calculation of the variables during the planning process (Ehrler et al. 2017). The model must therefore deal with a clearly defined and hierarchically arranged calculation methodology.

6.3. Warehousing and transshipment

The number of warehouses and the transshipment points depend, for example, on the geographical size of the distribution area, the customer's expected response time, the value of the goods stored, the lead time, the availability of transportation modes, and the respective transportation costs (Ihde 2001). The fundamental decision for warehousing in a new distribution region depends primarily on the expected supply service. Bundling effects in the production by the modification of the lot size or by the temporal decoupling of supply from transportation, however, can also lead to different warehousing strategies (Bretzke 2015). Additionally, transmission processes such as handling and stock picking, as well as the energy consumption of the required facilities, influence CO_2 emissions (Ehrler et al. 2017).

Besides the direct link to the decision variables of warehousing and transshipment, the geographical location determines the costs of transportation (e.g., for the last-mile distribution). As a result, an additional goal in the planning process could be to calculate the point where minimal transportation costs, minimal CO_2 emissions, or a specific service level could be achieved (Gudehus 2005; Mattfeld and Vahrenkamp 2014). Due to the high complexity provoked by these variables, the consideration of specific location factors and local conditions are being excluded in the early planning stages and postponed to later concrete planning and implementation processes (Schieck 2008; Bretzke 2015).

6.4. Additive manufacturing

Although the use of AM is now widespread due to its economic advantages, companies often do not have a well-defined understanding of how AM fits into their sustainability strategies. As already discussed in the previous chapters, AM has the potential to significantly lower life cycle energy demands of goods and their CO_2 emissions (Reeves, 2012). Manufacturing-related energy demands and CO_2 emissions are lowered through shortened processes and more direct manufacturing. This reduces the need for tooling (Petrovic et al., 2011) and the need for handling (Baumers et al., 2011). Shifting from a solely cost-focused approached to an integrated and coordinated approach, AM can improve the whole company's competitiveness and achievement of sustainability targets (Gebler et al. 2014). With respect to the impact on distribution systems, the company must decide on the location of the AM activities within the supply chain. AM can be located, for example, in a manufacturing plant, in a central or regional distribution center, or at the customer site for both parts of a product and the overall product (Feldmann and Pumpe 2016). Due to this model's goal of providing an expression comparison methodology, all variables related to the target dimensions of costs, time, and emissions need to be homogeneous. AM should therefore be an alternative beginning with the distribution of the deliverable products.

7. Development of the optimal distribution structure

7.1. Examination of structuring alternatives

Previous analyses of systems and functions of distribution logistics were described isolated from each other in the previous chapter. Because of these analyses, several systems could be excluded from further investigations so that the evaluation model is focused on road freight transportation, containerized line shipping services, air-freight, warehousing and transshipment, and customs as well as AM. According to Dircksen (Dircksen 2012), the isolated consideration of individual systems is not leading to the desired results in the planning of transportation chains. The process elements of transshipment and customs clearance are supposed to be considered in the model as process modules. In the model, the further forwarding of the sea freight and airfreight into the interior is completed, after transshipment and the release of customs, exclusively through road haulage. Furthermore, the model is supposed to contain the possibility of holding inventory in the target country for direct distribution, whereby the entire demand area is combined in one distribution area. The entire demand can therefore be distributed from one warehouse location in the target country. The supply of the warehouse occurs through replenishment processes that can be temporarily evaluated separate from the delivery time of customer orders. AM is an additional alternative for the distribution of products. To reach the advantages of the technology discussed in Chapter 3, it must be usefully implemented in the value chain. To take this into account, AM is embedded in the model at the latest stage of the process before customer delivery. After the AM process occurs in a central location, calculated by the minimal transportation costs approach (see Chapter 6.3), the products are transported to the final destination via road.

Once the individual process elements have been defined, these can be combined into a transportation chain. Five action alternatives then arise for the development of the distribution system. Alternatives 1 and 2 represent distribution systems with warehousing in the target country whereby the delivery of customer orders can be served directly from the domestic inventory. For Alternatives 3 and 4, no warehousing is planned in the target country. Alternative 5 is the option involving AM in the target country.

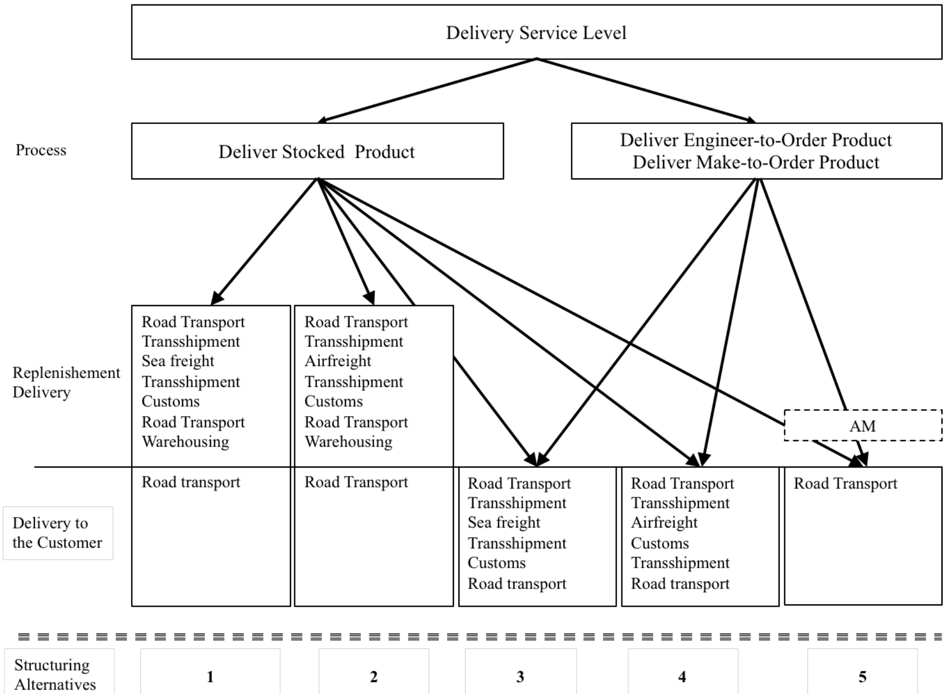

Fig. 9. Alternatives for structuring a distribution system.

The practical application of the model is calculated for a general and exemplary supply chain from Brazil to a German market. The product is a plastic spare part with a consumption rate of one item per year. The total demand is allocated to the ten biggest cities in Germany (*Statistisches Jahrbuch Deutschland 2017* 2017). The final destination for the transportation chain is a single distribution center in each city with a constant demand based on 50 calendar weeks. Figure 10 summarizes the respective parameters for the product to be distributed.

Description	Value	Unit
Total Demand per Year	6,253,342	products
Products per Pallet	3,120	units
Weight per Pallet	312	kg
Volume per Pallet	0.77	m³
Price/Value of one Product	3.50	€
Capital Commitment Rate	15	%

Fig. 10. Case Study: Overview of company-specific input parameters

For several years companies in Europe have identified cost pressure as the driving force behind logistics and supply chain management (Kersten et al. 2017). For the practical validation of the model, the authors follow this trend and assume costs as the primary decision factor, followed by the emission limitation defined in the delivery service, while complying with delivery times.

7.2. Determination of costs

According to the objectives, the decision model is supposed to help to find alternatives that can maintain the optimal design of total costs. Due to the different costs of the transportation modes and target conflicts between cost elements, for example, transportation costs vs. and inventory costs the target function is not linear. Additionally, the transportation operators developed different service types to fulfill customer demands, such as less-container-load

(LCL) for smaller transportation demands instead of full-container-load (FCL). In conclusion, only the total cost of the transportation chain, including transportation, inventory, warehousing, customs, and transshipment costs, is relevant to the decision. To validate the model, the authors collected a comprehensive data set of transportation and transshipment costs (see Figure 11).

Element	Transportation mode or service type	Cost factor
Precarriage on Road	Sea Freight – LCL	Rate per m^3 charge weight per region depending on departure seaport
	Sea Freight – FCL	Fixed rate per container per region depending on departure seaport
	Airfreight	Rate per kg charge weight per region depending on departure airport
Customs Export and Import	All Service Types	Per entry
Transshipment (before and after mainrun)	Sea Freight – LCL	Rate per m^3 charge weight per trade lane
	Sea Freight – FCL	Fixed rate per container per seaport
	Airfreight	Included in the mainrun rate
Mainrun	Sea Freight – LCL	Rate per m^3 charge weight per trade lane
	Sea Freight – FCL	Fixed rate per container per trade lane
	Airfreight	Rate per kg charge weight per trade lane
Oncarriage to Warehouse or delivery from Port/Airport to the destination on the Road	Sea Freight -LCL	Rate per m^3 charge weight per region depending on arrival seaport
	Sea Freight – FCL	Fixed rate per container per region depending on arrival seaport
	Airfreight	Rate per kg charge weight per region depending on arrival airport
Delivery from Warehouse to the final destination	Road - Groupage	Cost per charge weight cluster and distance cluster (matrix tariff)

Fig. 11. Case study: costs factors of logistic functions.

In addition to the transportation costs, for Alternatives 1 and 2 a warehouse must be integrated using a systematic approach. Before the replenishment costs can be calculated, the geographical warehouse location must be defined (Schulte 2013). The warehouse can be established with the help of the calculation process for the transport-optimal warehouse location. The goal is to find a place in an area with defined delivery points from where the sum of delivery costs for the distribution area is the lowest. Several calculation methodologies were developed to solve the mathematical problem, such as the Steiner Weber approach with the limitation of linear transportation costs (Domschke and Drexl 1996). Due to the non-linear groupage costs in the German transportation market, the authors solved the problem using a simulation approach. The result is a warehouse close to the city of Drolshagen (ZIP: 57489) in the triangle between Dortmund, Cologne, and Frankfurt in central Germany. The movement of the decoupling point by a delivery warehouse enables the implementation of a customer-neutral replenishment process in order to achieve bundling effects. The costs for inventory are moving opposed, whereby these can be decreased by ordering smaller replenishment lots. To follow the idea of the total cost optimum, the order lot size should be calculated using the tradeoff between the fixed replenishment cost factors and the inventory and warehousing costs (Thonemann and Albers 2010). The result for the transportation chain based on sea freight service type FCL-FCL was 27 containers per year and an average stock level of 115,803 pieces. The warehousing costs are calculated based on the floor space used per m^2.

In addition to transportation, warehouse and transshipment costs the products in the value chain tie up capital during transportation and warehousing. The capital charge in the warehouse is calculated by the average stock level multiplied by the production price plus the costs of operation according to the total costs of ownership (TCO) approach (Schulte 2013). The capital costs during transportation are dependent on the product value during transport and the transportation time. Figure 12 outlines the allocation of the total distribution costs for the yearly demand in the target market for the described Alternatives 1 through 5.

Structuring Alternative / Cost Element [Costs in EUR/Year]	1	2	3	4	5
Road (Precarriage)	5,996	15,515	41,340	15,515	
Customs Clearance (Export)	2,579	644	47,767	6,439	
Transshipment	6,586		10,546		
Sea Freight	15,660		79,900		
Airfreight		525,210		525,210	
Transshipment	6,750		51,000		
Customs Clearance (import)	675	707	3,102	7,070	
Road (Replenishment)	14,607	68,778			
Warehousing	62,359	6,176			6,176
Road (Distribution)	70,479	70,479	63,800	68,778	70,479
Capital charge (Transport)	326,285	103,450	419,495	93,800	9,120
Capital charge (Stocks)	65,834	9,645			
Total	**577,810**	**800,604**	**716,950**	**716,812**	**85,775**

Fig. 12. Total costs for Alternatives 1 through 5 for export from Brazil to Germany.

7.3. Determination of time

According to the objectives, the decision model is supposed to help to find alternatives that can maintain the required delivery service under the condition of optimal design of total costs calculated in the previous chapter. According to the prices of each cost element, the operators offer operation times for the service. When customer-built products are delivered, the estimation of the possible delivery time from the production to the final destination without warehousing is necessary. The delivery time is therefore often agreed upon with the customer in the order procession process – hence, before the signing of the delivery contract. The decision model is therefore assigned to determine the total throughput times from the origin to the final destination in Alternatives 3 through 5. In Alternatives 1 and 2, inventory is allowed in the distribution processes. The advantage of storing inventory in the target country is that the customer-related delivery time is reduced by the delivery from the warehouse to the final destination.

Structuring Alternative / Transport Time tTotal [Days]	1	2	3	4	5
Replenishment	35	10			
Distribution	1	1	46	10	1

Fig. 13. Replenishment and delivery time for Alternatives 1 through 5 for export from Brazil to Germany.

7.4. Determination of CO_2 emissions

Different uncoordinated efforts of standards agencies, industry bodies, and governments led to a large number of approaches and methodologies to measure emissions within logistics processes. Additionally, companies developed their own approaches due to the lack of guidance on measurement, analysis, and reporting (Auvinen et al. 2014). This diversity would not have been a problem had the numerous carbon-auditing schemes been based on a consistent set of principles. Efforts have therefore been made to reduce the diversity in order to harmonize carbon accounting in the logistics sector (McKinnon 2017). In general, two different approaches can currently be identified. The energy-based approaches are based on energy consumption and employ records of assets, converting them into emissions with reference to determined conversion rates. In contrast to these, the activity-based approaches multiply an index of the level of logistical activity by an industry-standard emission factor (Huang et al. 2017). In practice, companies are encouraged to adopt the energy-based approach whenever possible and should regard the activity-based approach with secondary data as the second-best option (Greene and Lewis 2016; McKinnon 2017). In addition the CO_2e summarize following gases CO_2, CH_4 and N_20 by the use of fixed conversion factors to broad the picture of the environmental impact (Greene and Lewis 2016).

The acceptance of EN 16258 as the first standard focusing on emission calculation for transports was the reason for establishing it as the central methodological item (European Committee for Standardization et al. 2012). This emphasis was further supported by the broad acceptance of the standard for transports inside and outside Europe (Auvinen et al. 2014). However, in the future, further efforts must tackle current restrictions such as the ambiguity of the choice of the transportation system, the differentiation in case of combined transports, and the lack of emission accountability with respect to functions other than transportation, such as warehousing and transmission (Auvinen et al. 2014). Regarding the additional functions in the transportation chain, fewer data sources and calculation methodologies exist for the emissions generated. For example, the environmental performance indicator (EPI) is a process-oriented approach and considers the main functions with the variables of energy, maintenance, and packaging. Those variables are multiplied by the number of processed or stored items and packages with less differentiation by activity, scale, and type (Rüdiger et al. 2016). The more heterogeneous the product range, the more difficult the allocation exercise becomes (McKinnon 2017).

In 2016, the Global Logistics Emissions Council (GLEC) published a process-oriented description model in combination with harmonized weighting factors. The "framework for logistics emissions methodologies provides a much more closely harmonized basis for the calculation of emissions from freight transportation chains across modes and global regions than existed previously" (Greene and Lewis 2016). The four-step evaluation process is divided into the steps planning, data collection, calculation, and use (Greene and Lewis 2016). According to this approach, the calculation methodologies must first be defined. Steps 2 and 3 should then be integrated into the presented model with the calculation of consumption factors and calculation of emissions for each leg. Finally, Step 4 accords with the comparison of the different distribution system alternatives defined in Chapter 7 of the present article.

Following the essential logistical functions, the bridged differences are a gap between supply and demand in the dimensions of time, distance, and quantity, which are fulfilled by transportation, warehousing, transshipment, and stock picking (Gudehus 2005). Following the structuring alternatives described in Chapter 7.1, calculation approaches of the functions are defined as follows:

Function / **Factor**	**Sea freight**	**Airfreight**	**Road**	**Transshipment harbor**	**Transshipment airport**	**Warehousing**
Volume	Calc. volume per container and no. of containers [1], [3]	Ton [2]	Ton [1]	Calc. volume per container [1]	Ton [7]	Square metre [7]
Bridged Difference	Actual distance [3]	Great circle distance [2]	Distance [3]	Picked volume / total volume [7]	Picked volume / total volume [7]	Time used [1]
Consumption Factor	FCL: global default value container vessel [3] for LCL: multiply with average payload [8]	Global default value hybrid aircraft [3]	EURO 5 truck; average payload EU [3], [5]	Energy consumption (electric power, gas, oil) [7], [8]	Energy consumption (electric power, gas, oil) [7], [8]	Energy consumption (electric power, gas, oil) [7], [8]
Emission Factor	International factor [4] - CO_2e – well to wheel	International factor [4] - CO_2e - well to wheel	Regional emission factors [6] - CO_2e - well to wheel	International factor; conversion factor CO_2 to CO_2e [4]	Average factor [7]; conversion factor CO_2 to CO_2e [4]	Average factor [7]; conversion factor CO_2 to CO_2e [4]

Fig. 14. Calculation of CO2e emissions (Sources: [1] (Dircksen 2012), [2] (International Air Transport Association - IATA (Montreal, Canada)), [3] (EcoTransIT World Initiative 2018) [4] (Greene and Lewis 2016), [5] (Wilmsmeier and Spengler), [6] (European Committee for Standardization et al. 2012), [7] (Rüdiger et al. 2016), [8] (Schmied and Knörr 2013)

After the definition the calculation approached the total CO_2e for the case study can be calculated.

Element [tons CO_2e / year] \ Structuring alternative	1	2	3	4	5
Road (Precarriage)	2.7	0.5	0.5	0.5	
Transshipment	0.8	>0.1	0.5	>0.1	
Sea Freight	54.0		61.5		
Airfreight		4,900.0		4,900.0	
Transshipment	0.8	>0.1	0.5	>0.1	
Road (Replenishment)	13.5	10.0			
Warehousing	0.8	>0.1			
Road (Distribution)	16.9	19.4	19.0	20.0	16.9
Total	**89.5**	**4930.0**	**82.0**	**4920.6**	**16.9**

Fig. 15. Total CO_2e emissions for Alternatives 1 through 5 for export from Brazil to Germany.

7.5. Determination of total result (costs, time, and emissions)

The question solved by the decision model was how AM can be implemented in an international value chain. Different alternatives were therefore defined where Alternative 5 includes AM. Figure 16 shows the result of the practical application for the supply chain from Brazil to a German market.

For processes with delivered stocked products, Alternative 1 with sea freight for replenishment and warehousing in the destination country is most beneficial due to creating the lowest emission costs and, from the perspective of service level, a short distribution time. Customer-specific products must be engineered or manufactured after the administrative customer order process has been fulfilled. The storage of finished products is not defined for engineer-to-order and make-to-order distribution processes (Supply Chain Council Inc 2012). In this scenario, the bundling effect and more cost-effective FCL/FCL cannot be archived, so the transportation chain with airfreight (Alternative 4) is the most beneficial alternative overall. In addition, the delivery time is considerably shorter, ensuring better delivery service. From the point of view of emissions, this scenario is problematic due to the length of airfreight transportation.

Element \ Structuring Alternative	1	2	3	4	5
Costs [EUR/Year]	577,810	800,604	716,950	716,812	85,775
Time [Days]	1	1	46	10	1
Emissions [Tons CO_2e/Year]	89.5	4,930.0	82	4,920.6	16.9

Fig. 16. Overview results of Alternatives 1 through 5 for export from Brazil to Germany.

The differences between Alternatives 1 and 5 for products in stock and Alternatives 4 and 5 for customer-specific products without warehousing show potentials through the implementation of AM in the dimensions of costs, time and emissions.

Process \ Potential	Costs	Time	CO_2e emissions
Stocked Product (Alternative 1 vs. 5)	492,035	0	72.6
Engineer-to-order, Make-to-order (Alternative 4 vs. 5)	631,037	9	4,903.7

Fig. 17. Potential for AM in different processes for the export from Brazil to Germany.

Showing a clear result for the three dimensions of costs, time and emissions in the described case of the exemplary international distribution, the applicability of the developed model was successfully tested. In addition, further case studies for the evaluation of the described model can be done. Furthermore, the focus can be expanded to other logistical processes like sourcing, production, customer use, maintenance and repair, or disposal and to the overall value-chain. However, the authors note that the variety of variables influencing the presented dimensions of costs, time and emissions will expand significantly. Streamlining the perspective means the calculated potentials in the distribution process can be understood as an element, or even as a first indicator, of a more extensive review as discussed in chapter 3.

8. Conclusions

The overall objective of this paper is to explain the main impacts of AM for economic decisions, including the perspective of ecological sustainability in global supply chains. To concretize this goal, two research questions were formulated:

- RQ1: How can the economic and ecological impacts of different scenarios be quantified in an early stage of planning a global supply chain in a holistic decision model?
- RQ2: What are the main impacts of AM on ecological sustainability over the different life-cycle stages of an AM-fabricated product?

The answer to the second question was found using a systematic literature review. At first, the overall classification of the dimensions cost, time, and emissions were analyzed in the process areas source, make, deliver, and return. The authors provided a structured overview of the ecological effects of employing AM, systemized according to the life cycle stages of an AM-fabricated object. To improve the competitiveness of the whole company and achieve sustainability targets, the delivery processes are the most promising with respect to the logistic functions due to the direct connection with the target market. Regarding the distribution processes' impacts on ecological sustainability, the sub-processes of the SCOR model "process warehouse activities" and "ship product" were accredited with the main effects on the environment. Based on those findings, the key research question of this paper (RQ1) a decision model is developed and validated by a practical case study.

The model illustrates a possible new evaluation standard because it ensures a clearly distinguished comparison of economic and ecological factors under the overall goal of reaching the coordinated service level. The core approach of the model presented in this article consists of an integrated supply chain perspective. Companies, scientists, and interested parties can use the model to create different distribution scenarios. Additive manufacturing has therefore been integrated as a structuring alternative. Finally, this approach utilizes a homogeneous comparison of distribution alternatives, leading to a gap analysis. The benefits calculated regarding economic and ecological aspects can cover additional affords in the other processes of the value chain. Using the case study of a distribution process from Brazil to Germany compared to the alternative of AM in Germany, the authors demonstrate the model's practical validity. Moreover, the model offers a high degree of flexibility, since the methodology allows for the estimation of variable factors. Through the addition of respectively process-relevant variables as required by the holistic mentality, meaningful results can be achieved that far exceed the isolated consideration of a single process or structural elements.

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