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3D Printers and Transport

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The Emergence of 3D Printing

3D printing (3DP) is a set of technologies that allows users to create products using digital models and an additive, layer-upon-layer manufacturing process. This new form of manufacturing is a marked shift away from shaping products from raw material as desired or from subtractive manufacturing methodologies, that is, constructing objects by cutting material away from a solid block of material. Trend watchers had already claimed that 3DP would lead to the next industrial revolution (Economist, 2016; Rifkin, 2011). Initial growth figures (2014–2016) did not match these expectations, resulting in disappointment (Deloitte, 2019). The last couple of years saw an increase in growth because of more diverse 3D printable materials (moving from plastics to metals), higher printing speed, and a gain in printing volumes. Short-term expectations already envision that the worldwide 3D industry will grow steeply, from $7.3 billion in 2017 to a forecasted $15.8 billion in 2020, and $35.6 billion by the year 2024. The growth is expected to come from more industrial 3DP systems, rather than desktop printers being sold (Wohlers Report, 2019).

3DP has been around for some time in the form of printed dental products, and has been adopted in other sectors that value production in small batches like hearing aids, and tailor-made jewelry and apparel (Rogers et al., 2016). In the context of product development in the automotive and aerospace industries, additive manufacturing has been used in the form of "rapid prototyping," that is, to make prototypes in a relatively fast way (Bradshaw et al. 2010).

Two recent developments are changing the scene of 3DP. First, the quality of additive manufacturing is increasing rapidly. Traditionally, 3DP was associated with lower quality, related to issues like geometric repeatability (degree to which a digital image can be reproduced), surface quality, and fatigue resistance (Huang et al., 2016). Scientific and technological advances are currently overcoming these issues (Gausemeier, 2014; Ngo et al., 2018). Second, the introduction of relatively cheap desktop 3D printers, such as RepRap, MakerBot, or Ultimaker, has made it possible for consumers to produce personalized home products such as jewelry and bicycle parts (De Jong and De Bruijn, 2013). With this, 3DP is moving from factory-based rapid prototyping to home fabrication (Rayna and Striukova, 2016).

3DP is thus associated with a more tailor-made, distributed way of manufacturing which, if successful, is bound to have repercussions on transport, supply chains, and logistics. But what is 3DP, how will it influence consumer wants and needs, location choices and transport resistance, and how will 3DP impact society? What are the repercussions for the transport and logistics sector? What is the state of knowledge, and which challenges are looming due to the emergence of 3DP? This article aims to answer these questions, of course taking into account the fact that the emergence of 3DP and its consequences are subject to a high degree of uncertainty.

The Concept of 3D Printing

The distinctive element of 3DP is building products layer by layer, rather than shaping from material (through forging, casting, stamping and molding) or subtracting from a block of material (through carving). 3DP should be understood as an aggregate of three elements: (1) the additive process technique, (2) the design and/or scanning software, and (3) the materials used (**Fig. 1**). The emergence of 3DP can be understood as an innovation pathway in which new developments are happening on all of these three elements, as well as in the combinations of these elements (Robinson et al., 2019).

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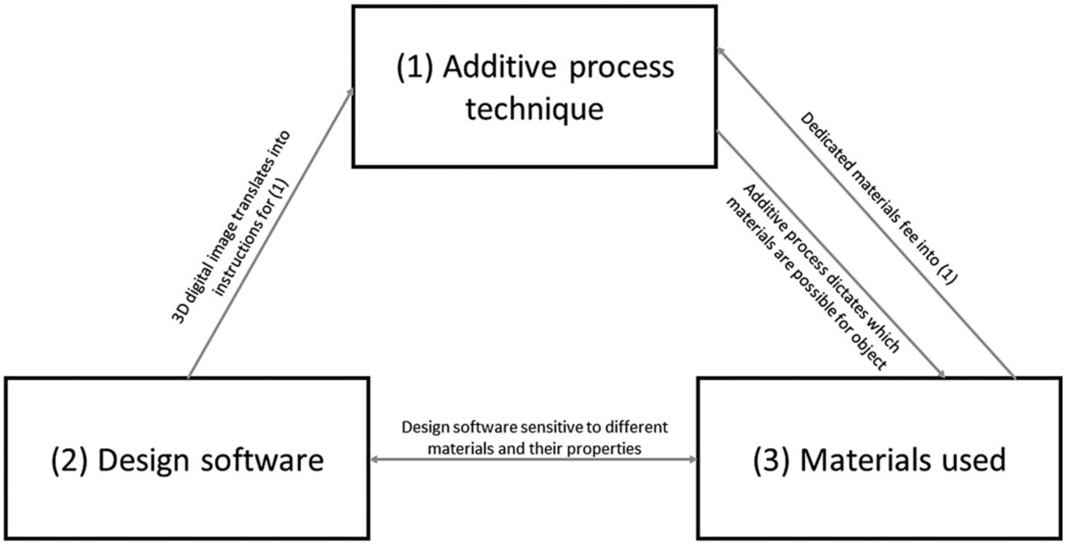

Figure 1 The three main elements of 3D printing. *Source: Adopted from Robinson et al. (2019)*

The first working 3D printer built in 1986 by Charles Hull was based on stereolithography. Since then, various additive process techniques [(1) in **Fig. 1**] have been introduced (**Table 1**). The movements of the printers, as well as the size and form of the successive layers that need to be printed to fabricate the 3D object, are dictated by 3D modeling software, often in the form of computer aided design (Griffiths, 2002).

Influence of 3D Printing on Transport and Logistics

The influence of 3DP extends from manufacturing to include changes in logistics and transport. The recent cost reduction and availability of easier-to-use printers have led to expanding the customer base to also include households, schools, libraries, and so on. Such an expansion might result in a decentralization of production (Holmström et al., 2010). The transition from centralized to decentralized manufacturing has repercussions for transport flows (Ford and Despeisse, 2016) and related supply chain management and business models of involved companies (Bogers et al., 2016).

To better understand the potential influence of 3DP on logistics, a literature review was conducted of 93 scientific articles and 12 reports of leading consultancies. Based on the review and a survey amongst experts on 3DP and logistics, a model was created that

Table 1 Summary of different 3D printing techniques

Technique	*Short description*	*Application areas*	*Introduced since*
Stereolithography	Photochemical process of UV laser causing monomers to link together to form polymers	Biomedical Prototyping	1986
Fused deposition modeling	Thermoplastic material filament fed through a moving printer extruder head, the shape of which is digitally controlled to define the printed object	Rapid prototyping Toys Advanced composite parts	1988
Powder bed fusion	Fusing thin layers of powder with use of lasers	Biomedical Electronics Aerospace Lightweight structures (lattices) Heat exchangers	1993
Inkjet printing and contour crafting	Powder pumped and deposited in the form of droplets via a nozzle to form a continuous pattern	Biomedical Large structures Buildings	1993/2011
Direct energy deposition	Energy source like lasers is focused on a substrate simultaneously material	Aerospace Retrofitting Repair Cladding Biomedical	1995
Laminated object manufacturing	Adhesive-coated material (paper, plastic) is glued together and cut into shape	Paper manufacturing Foundry industries Electronics Smart structures	1996

Source: Based on Ngo et al. (2018)

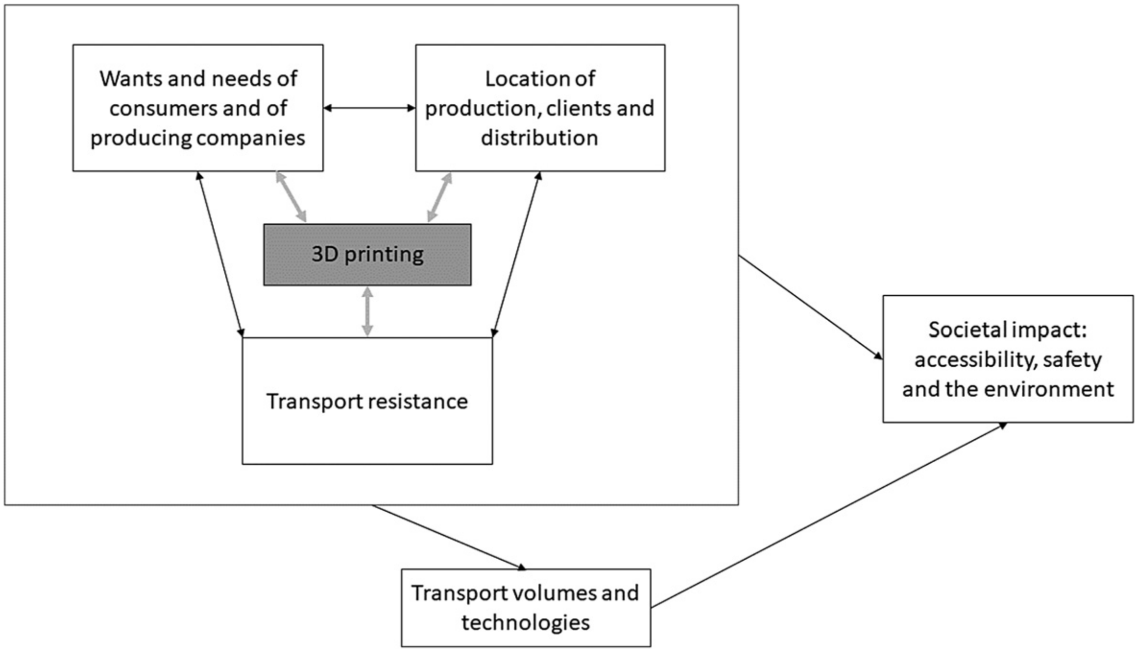

Figure 2 Conceptual model for the impact of 3D printing on logistics and eventually on accessibility, the environment and safety. *Source: Adapted from Boon and van Wee (2018)*

conceptualizes the influence of 3DP on logistics, and subsequently on societal impacts in terms of accessibility, traffic safety and sustainability (Boon and van Wee, 2018). The model is shown in **Fig. 2**.

Each element of the model can be elaborated upon, first zooming in on the influence of 3DP on wants and needs, location decisions and transport resistance. Subsequently, transportation volumes and technologies are addressed and, finally, the way in which accessibility, sustainability and safety are influenced.

Wants and Needs of Consumers and of Producing Companies

3DP was originally used to produce one-offs in professional settings like the abovementioned rapid prototyping in aerospace and car industries, or creating personalized models of skulls that can be used for preparing for complex surgery. Increasingly, 3DP is utilized to cover both prototypes and finalized products. The latter include examples like in-ear hearing aids and dental parts, as well as small consumer products, like jewelry and toys. Close to adoption are applications like spare parts in the aircraft and surgical industries. Consumer products are especially restricted in their impact and some authors claim that 3DP will remain having a limited effect (Fawcett and Waller, 2014; Gress and Kalafsky, 2015). More complex products remain comparatively rare, because of questionable efficiency and added-value to consumers (Mckinnon, 2016).

Literature and the experts who were surveyed were in agreement about the fact that mass-customization will become more important. There are different points at which the customer may become engaged in the supply chain, at each stage of the supply chain: design, purchasing, fabrication, assembling and distribution (Gosling et al., 2007). 3DP plays a significant part in customer-specific design and manufacturing, since it has the possibility to pursue product customization and a fast response to customer needs, as a result of flexibility and adaptability (Bhattacharjya et al., 2014; Chan and Chan, 2010; Christopher and Ryals, 2014; Janssen et al., 2014; Lopes da Silva and Vicente, 2013). 3D-printed prototypes can help increase user understanding early in an innovation process, decreasing time-to-market and risks of non-adoption (Kanto et al., 2014; Romero and Vieira, 2016). Companies might respond by making their supply chain and related production capacities more flexible and agile (Sasson and Johnson, 2016).

A related development is the rise of 3D platforms that offer, amongst other things, free-to-use design files (www.thingiverse.com) or offer a place to share 3DP capacity (www.3dhubs.com). Such platforms can increase the possibilities of personalization and the ability to deliver to the "long-tail" of consumer needs (Bogers et al., 2016). Moreover, these platforms are often two-sided, that is, consumers both use the presented products (e.g. designs) as well as offer their own creations. As such, 3DP ties into the development of consumers becoming producers, acting as "pro sumers" (Chen et al., 2015; Rauch et al., 2016).

The experts interviewed (Boon and van Wee, 2018) were divided on the issue as to what extent consumers are willing to really manufacture a wide range of products at home, or whether new needs for different kinds of products will emerge. Also, opinions about the frequency of buying were split: some experts say that frequency will increase, because customized products follow trends and are disposed of more quickly; additions are replaced more easily. Others claim frequency will decline, because customized products do not need to be replaced and if broken, small parts can be reprinted.

Location of Production, Clients and Distribution

3DP advances mass customization and personalization (Bhattacharjya et al., 2014; Mourtzis and Doukas, 2013). The question central to many articles and trend reports is to what extent 3DP leads to distributed production. Two extreme scenarios can be sketched: decentralized versus centralized manufacturing (Li et al., 2017). Most publications envisage that 3DP will result in more decentralized manufacturing, offering greater proximity to customers and responsiveness to market needs (Fornasiero et al., 2010; Manners-Bell and Lyon, 2012), possibilities to cut out middlemen (Jia et al., 2016), and even the reshoring of manufacturing to high-income countries (Campbell et al., 2011). Designs travel digitally (Janssen et al., 2014) and as such can replace the movement of products (Garrett, 2014).

In the decentralization scenario, the locations of 3D printers will vary, ranging from "print shops" serving markets at a continental scale, city- or neighborhood-level hubs to printers located at consumers' homes (Rauch et al., 2016; United States Postal Service Office of Inspector General, 2014). Ryan et al. (2017) produced a different, yet related taxonomy of decentralized 3DP scenarios: mobile, in-transit 3DP; 3DP for standardized spare parts; local and regional factories; craft businesses, like "fablabs," and personal manufacturing.

An in-between scenario is that 3D "mini-factories" are located at local service providers such as libraries, community centers and post offices, as such mimicking 2D printing of photos and books. It is also expected that 3D logistics service providers will enter the additive manufacturing market within the next ten years (Durach et al., 2017). Hub-level operations have the advantage over home-based printing, because 3D printer (machine) operation, post-processing, quality control and (consumer) packaging require investments and expertise that home-print consumers are not going to develop. Much is expected from the product customization, agility and even complexity that 3DP hubs can yield, which are associated with specialization, lower time-to-market and even lower costs (Rogers et al., 2016).

Some industry watchers still emphasize the importance of centralized production. High-volume, low-added-value production will remain more efficient in centralized factories (Holmström et al., 2010; Li et al., 2017). Also, low-volume and high-added-value manufacturing require support infrastructure and specialized human resources (Gress and Kalafsky, 2015). The degree of centralization involves a complex interplay of economies of scale, as well as user requirements, regarding flexibility, adaptability, demand uncertainty, supply uncertainty, and capacity utilization. For example, in spare part management in the field of aircraft maintenance there are parts that are not used very often, "slow-moving parts," yet when required they are needed fast. In these cases, 3DP might provide a solution (Fawcett and Waller, 2014; Holmström et al., 2010; Huang et al., 2013).

In the end it may very well be that the two "extreme" scenarios are combined and are deemed complementary. A hybrid scenario could be that more advanced 3DP will (mainly) be done at centers, and that simpler printing will be done at home. For such hybrid scenarios to be pursued, it is important to think about communication, information exchange, intellectual property rights, and quality control between centralized and decentralized entities. Advancing digital innovation may facilitate managing this (Durão et al., 2017). Companies will vary in the business models they adopt, but experts expect the hub model to be favored over competing approaches and to emerge as the dominant business model (Boon and van Wee, 2018).

Transport Resistance

The location of 3DP dictates the nature and size of transport flows. 3DP taking place closer to home is related to a decrease in distribution between manufacturing and end users (Janssen et al., 2014; Tuck et al., 2007). Even shipping and air cargo volumes might come down (Barz et al., 2016; Manners-Bell and Lyon, 2012). As input to decentralized 3DP, shipments of raw materials will become more important. This would mean a shift from manufacturer–consumer distribution to the raw material supplier–-manufacturer side (Gress and Kalafsky, 2015; United States Postal Service Office of Inspector General, 2014). Moreover, the transport of raw materials can be more efficient, since bulk delivery means less packaging and urgency, leading to a reduction of ton-kms and cubic meter-kms of freight movements (Mckinnon, 2016). Distribution networks will be organized more efficiently: with more nodes and more flexibility. Transport and logistics costs may come down as production happens closer to home and feedstock is transported more efficiently in the form of cartridges, leading to less air to be transported on the outbound-shipping part of the chain. Relatedly, 3DP has an impact on warehousing. Less inventory might result from less variety in input materials needed, less safety-stock, and consumers being dedicated in their needs (Mavri, 2015).

Still, some experts think that transportation costs may actually increase (Boon and van Wee, 2018; Durach et al., 2017). Raw materials will need to be shipped to 3D printers located at "mini-factories" or hubs. Then the distribution between hubs and consumers' homes might spur short-distance "last mile" express delivery that is associated with higher flexibility in distribution and higher costs (Mohr and Khan, 2015). Even so, different types of costs can also balance each other out: for example, Westerweel et al. (2018) found that the higher design costs related to 3DP are offset by reduced after-sales logistical cost and lead-times.

Transport Volumes and Technologies

3DP might lead to the transportation of more raw materials, for example in the form of gels and powders contained in packaged cartridges. This, then, means a shift away from shipping ready-made consumer goods, the transport of bulk inputs for 3D printers will become more important and might mean less need for the use of containers. On the other hand, experts say that other emerging technologies, such as electrification and autonomous driving, are far more influential on how transport technologies of the future will look. An interesting, left-field idea is to have 3DP manufacturing onboard a driving truck, which opens up the possibility of creating products just-in-time for delivery (Ryan et al., 2017).

In terms of transported volume, there are reasons to assume that there will be a decrease because of extended product-life-in-use, less air to be transported, and a reduced number of kilometers in the last mile. There are also reasons for an increase in transport volumes as there is more material that needs to be cut out, and subsequently returned. The timing of deliveries to consumers might change. On the one hand, there may be more deliveries outside office hours, whereas on the other, brand new ways of dispatching can emerge, such as smart letterboxes.

Societal Impact: Accessibility, Safety, and the Environment

The literature has been silent about the effects of 3DP on traffic safety, accessibility, infrastructure needs, and the indirect effects on passenger transport. Concerning welfare, income, and employment, 3DP may be regarded as having a potential disruptive impact on the global transport sector (Bogers et al., 2016). The total system costs may not drop because labor and transport costs are communicating vessels (Chan and Chan, 2010; Manners-Bell and Lyon, 2012). For example, 3DP might lead to "reshoring" of manufacturing to high-income countries, especially as 3D printer hubs are to be located closer to customers (Frazier, 2014; Janssen et al., 2014). At the same time, this would require the creation of highly skilled jobs in these hubs (PWC, 2014). Traditional outsourcing countries may not be disadvantaged by reshoring, as experts claim that they are increasingly becoming capable to become frontrunners in 3DP as well (Gress and Kalafsky, 2015).

In terms of the environmental impacts of 3DP, there are model-based studies that hone in on material usage and waste (Campbell et al., 2011; Huang et al., 2016; Romero and Vieira, 2016; Barz et al., 2016; Garrett, 2014; Li et al., 2017; Lopes da Silva and Vicente, 2013). Less is written about logistics and transport-related environmental impact. Some publications make tentative predictions that emissions and oil use will be reduced (Bhattacharjya et al., 2014; Ford and Despeisse, 2016). Proposed hypotheses are that due to production closer to home, long-distance transport can be reduced and distribution of raw materials can be made more efficient. Last-mile movements might increase but if they are done by low-emission vehicles, then this means less

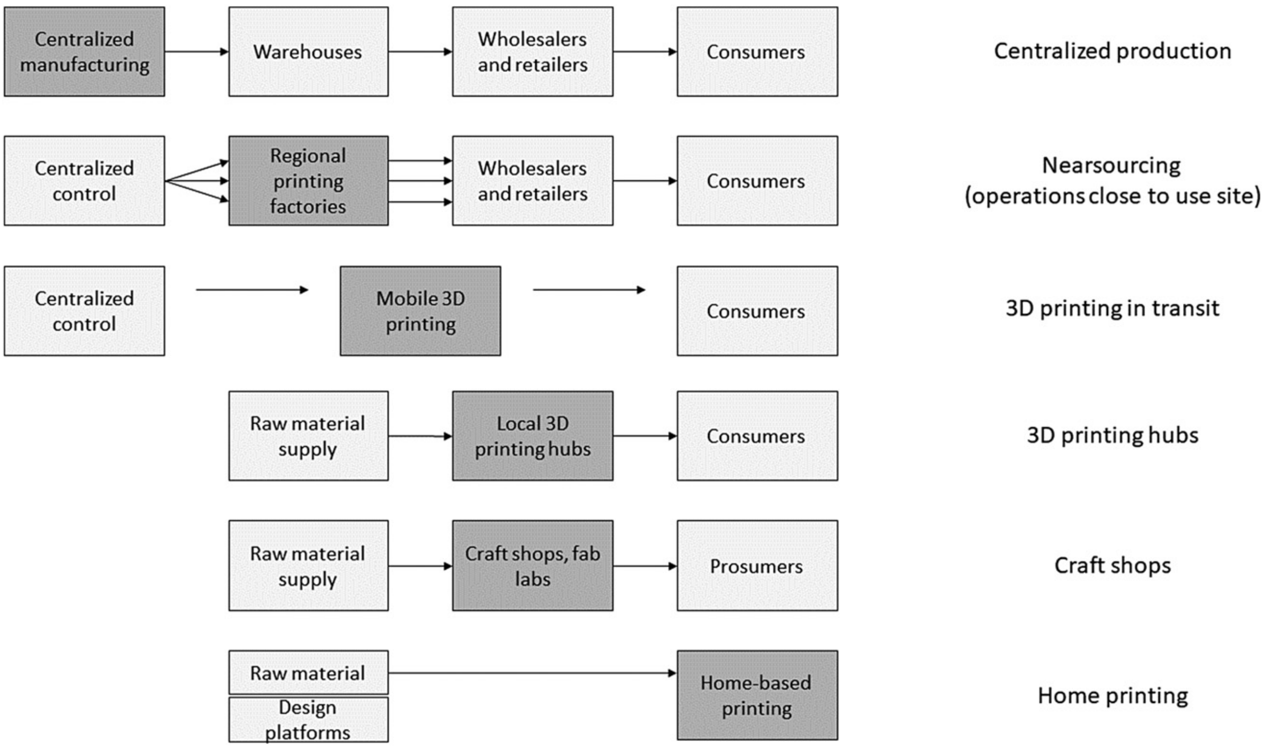

Figure 3 Spectrum of possible 3D printing locations.

emissions (Chen et al., 2015; Rauch et al., 2016). 3DP might, due to its production-on-demand model, lead to reduced inventory waste and greater potential for recycling (Despeisse et al., 2017; Ford and Despeisse, 2016). On the other hand, the logistical network might also become less efficient: "a change from standard to individualized, highly responsive logistics services [. . .] will lead to less sustainable logistics systems" (Tavasszy et al., 2003).

Discussion

How the future of 3DP will look is largely dependent on the interactions between end-user needs and wants, location decisions, and transport resistance. 3DP is associated with the personalization of products and might tie in with developments like mass-customization. Of course, not all types of products are equally suitable for personalization and in some cases small batches are not (cost)efficient. Still, in some sectors like aerospace and medicine, small batch 3DP is widely adopted, and other sectors might follow suit. As such, 3DP is expected to result in decentralization, although the exact nature of decentralization is still open for discussion. One may see the location of 3DP as part of a spectrum, ranging from centralized production all the way through to home-based printing (**Fig. 3**). Obviously, the exact outcome is dependent on factors like type of product to be manufactured, type of material, etc. Since there are a wide variety of consumer needs as well as types of materials and products, most likely a hybrid scenario will unfold in which different forms of 3DP in different locations are coexisting.

The emergence of 3DP and the associated decentralization of manufacturing will impact the transport and logistics sector in several ways:

- Transport volumes might not necessarily decrease, but delivery times and transport costs are expected to decrease.
- In terms of transport flows and movements, distribution networks are expected to be organized more efficiently. Distributed manufacturing still means that raw materials need to be shipped to decentralized locations. However, the transport of raw materials is expected to be more efficient, as they are moved in bulk in forms like cartridges, leading to less empty vehicles.
- The way inventories are kept will change: the size of inventories might decrease, amongst other things, because goods are now made to order and because safety-stock is not needed. Especially in the area of service parts, there are new opportunities for the instantaneous production of spare parts. Associated with this is the fact that suppliers run less risk of keeping products in stock that are never sold.
- The roles and positions of companies in the value chain will shift. In some scenarios some intermediaries, such as wholesalers or even retailers, might become superfluous. Some shops will vanish altogether or change into places to showcase products. At the same time, companies might strategically make upstream or downstream movements. Logistics companies might move into decentralized production by opening 3DP hubs. For example, postal services can turn their post offices into printshops and use their distribution networks to provide last-mile deliveries (United States Postal Service Office of Inspector General, 2014). Another example is wholesalers starting to emphasize stocking and delivering raw materials needed for home-based printing.
- Even if the roles of the companies in the value chain remain unchanged, the exchange of information will be affected. 3DP emphasizes agile development, on-demand production and customization, which means that customers are increasingly submitting personalized designs, either created on their own, or based on designs available on internet platforms. Design information needs to be sent to the 3D printer and probably checked before manufacturing can begin. Related to this, control over intellectual property rights and unwanted products is a challenge, as design platforms consist of propriety designs and there was commotion about the creation of a design template for a 3D-printed gun.
- Thus digitalization is becoming more important, because the design of products may move from end users to printing hubs, or from centralized companies to near-shored printing hubs (**Fig. 2**). There is a large role for quality control in this process: decentralized production still needs to adhere to quality standards imposed by the company and/or the government (e.g. in the form of safety and the environment).

Concluding Remarks

This contribution set out to explore the influence of 3DP on transport and logistics. More specifically, it dealt with how 3DP will influence consumer wants and needs, location choices and transport resistance. It has also addressed what are the repercussions for society and, specifically, the transport and logistics sector. Experts and industry watchers claim that 3DP has the potential to disrupt industries, including the transport and logistics sector. 3DP is an emerging technology, meaning that many aspects, like demands, networks and the technology itself, are under development, malleable and uncertain. Crucial factors of 3DP are the decentralization of manufacturing locations and the on-demand and agile nature of consumer demand. These two cornerstones will influence the way supply chains are organized and how logistics is organized. In turn this might then influence transport flows and related impacts on society in terms of safety, accessibility and the environment, as well as the nature and survival of firms in the value chain of many industries. Monitoring of the developments of 3DP in relation to transport and logistics is crucial, because it might have consequences for infrastructure, regulation, the capacity of logistics hubs like ports and harbors, and many more.

Biographies

Wouter Boon is Assistant Professor in Innovation. He works at the Innovation Studies group that is part of the Copernicus Institute of Sustainable Development, Utrecht University. His research in the field of innovation studies focuses on the dynamics and governance of emerging technologies in science-based sectors, such as transport and life sciences. The theoretical focus of his work is on the role of user innovations, user-producer interactions, regulation, and knowledge production in emerging technology fields.

Bert van Wee is Professor in Transport Policy at Delft University of Technology, the Netherlands, faculty Technology, Policy, and Management. In addition he is scientific director of TRAIL research school. His main interests are in long-term developments in transport, in particular in the areas of accessibility, land-use transport interaction, (evaluation of) large infrastructure projects, the environment, safety, policy analyses, and ethics.

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