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Influence of 3D printing on transport: a theory and experts judgment based conceptual model

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ABSTRACT

Consumer 3D printing is on the rise and has the potential to significantly change the transport and logistics sector. Current literature on 3D printing and transport studies does not provide a systematic model of the impact of 3D printing on transport and related (policy relevant) areas, such as traffic safety, location decisions, accessibility and environmental effects. Based on a literature review and two rounds of expert consultation, we propose and refine a conceptual model as a way to approach this gap in the literature. The expert consultation yields that the conceptual model comprises the relevant and important elements for assessing the impact of 3D printing on transport and transport-related challenges. Location, needs and transport resistance are important: (a) city-level hubs are the most likely locations for 3D printers because they can coordinate material flows and gather expertise; (b) mass-individualisation and personification dictates the needs for 3D printers; (c) distribution networks will be organised more efficiently, less empty vehicles, but raw materials still need shipping. However, experts' opinions diverged on the impact of 3D printing on transport volumes and environmental impacts.

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3D printing; environmental impact; location choice; customer needs; literature review; expert judgment

1. Introduction

3D printing as a new form of manufacturing is on the rise. Developments in the past decade have the potential to disrupt construction and production industries and some commentators even go to the extent to claim that 3D printing will lead to a third industrial revolution (Economist, 2016; Rifkin, 2011). Some forms of 3D printing have been there for quite some time, such as printing crowns, bridges and stone models in dentistry. Rapid prototyping has been around for decades and was intended to produce prototypes in a relatively fast way in e.g. the automotive industry but also in healthcare and aerospace (Bradshaw, Bowyer, & Haufe, 2010). The advent of relatively cheap desktop 3D printers, such as RepRap, MakerBot or Ultimaker, has made it possible for consumers to produce personalised home products such as jewellery and bicycle parts (De Jong & De Bruijn,

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2013). In the context of tissue engineering, biofabrication is possible: now scientists are able to print cartilage or constructs that function as blue prints of tissue, but printing complete organs is still something for the far future (Murphy & Atala, 2014). Currently, 3D printing is moving from factory-based rapid prototyping to home fabrication (Rayna & Striukova, 2016).

3D printing is a subset of additive manufacturing, which can be defined as a way to build objects by adding – or joining – material in a layer-by-layer fashion. This way of fabrication is in contrast with the conventional subtractive manufacturing, i.e. making final products by removing material in a controlled way. The quality of 3D printing is still wanting, including issues with geometric repeatability, residual stresses, surface quality and fatigue resistance (Huang et al., 2016). Still, advances in the scientific and industrial communities are expected to overcome these problems in the next 5–20 years (Gausemeier, 2014).

Three elements of 3D printing are important to describe the additive manufacturing process. First, the 3D printer itself: since the first working 3D printer built in 1986 many types of printers have been developed, based on technologies like stereolithography, fused deposition modelling and laser sintering. Second, the materials used for printing, which range from plastics and metal to concrete and even biomaterial (Murphy & Atala, 2014). Third, the printer needs design input. Often, 3D modelling software in the form of Computer Aided Design (CAD) is used. The resulting 3D model dictates the movements of the printer's nozzle and prescribes the size and form of the successive layers that need to be printed to fabricate the 3D object (Griffiths, 2002).

3D printing impacts the way in which products are manufactured, which has potential impact on other segments of society. One of these aspects is transport and logistics. The promise of 3D printing includes the transition from centralised to decentralised manufacturing and supply chains (Holmström, Partanen, Tuomi, & Walter, 2010). The decentralisation has repercussions for transport flows (Ford & Despeisse, 2016) and supply chain management and business models of involved companies (Bogers, Hadar, & Bilberg, 2016).

Current literature on the impact of 3D printing focused on the possibilities and qualitative repercussions for future business models and society in general (e.g. Fawcett & Waller, 2014; Gress & Kalafsky, 2015; Tuck, Hague, & Burns, 2007). Mostly, the impact on for example sustainability has been analysed on a broad level, or concentrated on material and energy consumption (Barz, Buer, & Haasis, 2016), and not so much on the role transport plays. In terms of logistics, implications of 3D printing are mostly researched for companies, leaving the impact on the wider manufacturing and transport sector nascent (Holmström, Holweg, Khajavi, & Partanen, 2016; Kohtala & Hyysalo, 2015; Laplume, Petersen, & Pearce, 2016). There is need for gaining more insights into the impact of 3D printing on supply chains, and how 3D printing providers should position their manufacturing facilities is scarcely investigated (Rogers, Baricz, & Pawar, 2016). Also, these changes in distribution have impacts on policy relevant effects on society, important effects being on congestion and reliability of traffic, safety and emissions. So, current literature on 3D printing and transport studies does not provide a systematic model of the impact of 3D printing on transport and related (policy relevant) areas such as traffic safety, location decisions, accessibility, environmental effects, infrastructure needs, welfare, income, employment, consumption patterns and satisfaction (Chen et al., 2015; Ford & Despeisse, 2016; Frazier, 2014).

This paper aims to fill this gap, and explores the impact of 3D printing on transport and transport-related issues by proposing and validating a conceptual model that covers these elements. To this end, we developed a draft conceptual model based on literature (mainly theory) and then validated the model based on expert judgments. The next section offers the methodology applied in this paper. The literature overview in Section 3 forms the starting point for the exploration of the significant concepts that are part of an a-priori conceptual framework. This framework was shared with a confined group of experts. The product of this expert consultation is a revised conceptual framework that is presented in Section 4. Section 5 contains the conclusions and discussion based on a wider consultation of the model.

2. Methodology

The methodology we adopted is visualised in Figure 1. The steps (I–III) are explicated below.

2.1. Literature review

The literature review (I in Figure 1) on the impact of 3D printing on transport and logistics demands a cross-section of two domains, i.e. between transport (transport, traffic, logistics, accessibility, mobility, supply chain, …) and 3D printing (additive manufacturing, 3D printing, rapid prototyping, distributed manufacturing, rapid manufacturing, …). The appendix presents the six strategies we followed to search Scopus.

After excluding overlapping articles, we ended up with a list of 93 publications. Of these 93 publications, references to interesting other publications were noted and subsequently included in our sample. This backward "snowballing", i.e. looking at papers that are cited in

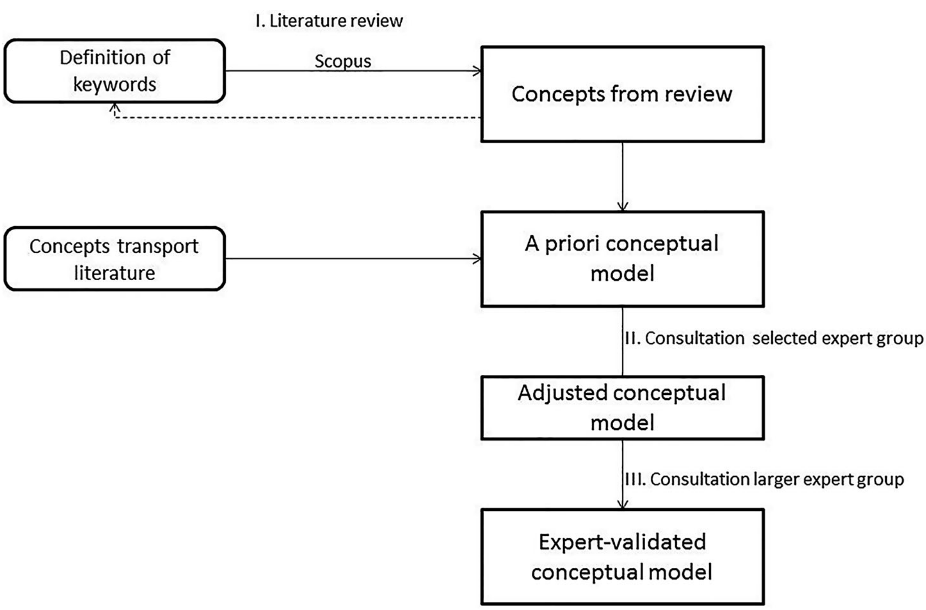

Figure 1. Overview of the methodological steps taken to produce an expert-validated conceptual model.

the original set of 93 papers, led to the inclusion of another 12 publications and reports. Most of these additional publications were foresight and trade reports by consultancies, financial institutions, companies (such as postal services) and key opinion leaders. Because reports add to the academic perspective and are more up to date, we also performed a search on Google and Google Scholar, which returned six additional publications. Backward snowballing, i.e. looking at the publications that cited the set of papers found, did not yield additional publications; papers had already been included and most were quite recently published so they were little cited yet. Because we are interested in the impact of 3D printing on transport, the final set of 111 publications was then analysed using the transport themes that were introduced in the first section, such as location choices, mobility and user needs, as well as policy relevant effects of the transport system, such as accessibility, the environment and safety. We allowed for additional themes to emerge from the data if these themes showed a strong link with transportation. To ensure that all publications were searched for the emergent themes, publications that had already been analysed were re-read. The literature review is reported in Section 3.

2.2. Consultation of selected expert group

A draft conceptual model was designed, largely based on transport literature and the literature view. The draft conceptual model was sent to three logistics and transport professors for validation (II). These are academic experts in the area of strategic developments in goods transport. We selected the three experts because one of the authors of this paper knows them well, increasing the likeliness that they did very carefully evaluate the draft framework. The aim was to improve the conceptual model so that all dominant dependent and independent variables and their relationships were included. The answers of the experts in this round consisted of both feedback remarks about the model and about the content of the variables in the model. We treated these two kinds of answers separately although sometimes answers fell into both categories (e.g. being unable to answer a question because the variable is not regarded as relevant to the expert). Based on the Likert-scale scores, we were able to analyse what the majority of the respondents think, as well as what the minority position is. We reported these majority–minority positions alongside striking and insightful answers. Because of the small sample size, we were able to report a wide variety of these qualitative answers (Bryman, 2015). We developed a revised version of the model based on the reactions as described in Section 4.2.

2.3. Consultation of larger expert group

The revised conceptual model was sent to a larger group of experts (III), excluding the ones from the first round. The aim of this stage was to obtain rough indications of (a) the underlying assumptions and (b) the quantitative effects. We selected these experts through two routes. First, we asked the experts of the first round for a list of experts. Second, we selected experts based on the literature review. We took the sample of 60 publications included in the review and selected 26 publications that explicitly dealt with 3D printing and transportation and logistics. We sent the questionnaire to the first authors of whom we could find e-mail addresses. In some cases, we ended up with the second or last author. In total, we sent the questionnaire to 24 people, of which 10 answered the questionnaire. These experts are affiliated with universities, public R&D institutes, consultancy companies and logistics companies, and are knowledgeable in the area of strategic developments in goods transport. The questionnaire was tested amongst the authors and with one respondent before sending it out to the complete sample. In the questionnaire we presented propositions, and asked the respondents to score on a 5-point Likert scale, ranging from "strongly disagree" to "strongly agree". The propositions were derived from the revised conceptual model (after stage II), and in terms of the description of effects of 3D printing as presented below in Section 4. The estimations on quantitative effects were obtained by asking the experts to score the "arrows" in the model, answer categories being "a large negative effect", "a small negative effect", "no or only minor effects", "a small positive effect" and "a large positive effect". "Large" was defined as a change of >10% on the dependent variable, small as a change of 5–10% on the output variable and the middle/moderate category as an effect of between minus and plus 5% effect on the output variable. "Negative" was defined as a decrease in the value of the dependent variable. So, a "negative" effect on CO_2 emissions means a reduction of those emissions, which is generally considered to have a positive effect on society. At the end of the questionnaire, there were open text boxes in which the respondents could provide general opinions about the validity of the model (recommendations, suggestions for improvement, etc.). The analysis of the consultation is similar as with the smaller group of experts (see above). To provide more insights into the majority–minority positions, we indicated how many respondents supported a certain claim ("*x* out of 10 respondents; *x*/10"). The results of this consultation round are reported in Section 4.3.

3. Results of the literature overview

The resulting set of publications that formed the basis of our literature search is quite heterogeneous. The 111 publications that were used included journal articles (98), a book (1) and reports (12). The reports were mostly written by consultancy firms, financial institutions and transport industry experts. These publications cover different types of research, e.g. reviews (28), modelling (12) and future foresight exercises (6). As the large number of review articles signifies, the included studies are mostly based on secondary data. Only a minority gathered own data, most of which focusing on particular cases; only three articles used a survey. This means that nearly all publications included in the search set are forward-looking, visioning documents rather than based on concrete figures. Content-wise, there is quite some emphasis on what 3D printing means for consumers, distributed manufacturing and supply chain management, tissue engineering, 3D printing in particular contexts (such as libraries or laboratories) and life cycle analyses of additive manufacturing. Table 1 presents information about the bibliometric scope of the publications.

Below, we discuss the literature distinguishing the potential impacts of 3D printing on traffic flows and on policy relevant effects.

3.1. Impact on transport flows

The publications addressed *user requirements* and *consumption patterns*. Influences on consumer patterns depend on the types of products involved. Our review shows that

Table 1. Bibliometric scope of publications used.

Authors	Year	Type of research	Journals
Fawcett S.E. 4	2014 33	Review 28	*International Journal of Production Research* 7
Waller M.A. 4	2016 21	Modelling 12	*Journal of Business Logistics* 5
Holmstrom J. 3	2013 12	Foresight 6	*Journal of Cleaner Production* 5
Pearce J.M. 3	2015 10	Conceptual paper 5	*Technological Forecasting and Social Change* 4
Baumers M. 2	2012 6	Cases 4	*IFIP Advances in Information and Communication Technology* 4
Chan H.K. 2	2010 5	Experiment 3	*International Journal of Physical Distribution and Logistics Management* 3
Despeisse M. 2	2011 3	Survey 3	*International Journal of Production Economics* 3
Hague R. 2	2006 3	Essay 2	*Logistics Research* 3
Hao L. 2	2008 3	Research agenda 2	*First Monday* 2
Kostakis V. 2	2009 2	Storytelling 2	*Journal of Manufacturing Technology Management* 2
Kreiger M.A. 2	2004 2	Workshop 2	*Production Planning and Control*2
Mourtzis D. 2			*PICMET 2014* 2
Partanen J. 2			
Rayna T. 2			
Striukova L. 2			
Tuck C. 2			
Wang X. 2			

current 3D printing mostly uses metal, polymers, ceramics, wax and cells as input materials. Present applications are in in-ear hearing aids and dental parts, small consumer products like jewellery and toys, and rapid prototyping in aerospace and car industries. Direct additive manufacturing (making reliable spare parts in aircraft industries) and surgical implants (with surfaces on which tissue can grow) are close to adoption, whereas bioprinting (replacement organs) and more complex desktop-scale 3D printing are expected in the future. It seems that current professional applications are mostly one-offs, focused on prototyping and complex products. Consumer applications are limited to small-impact products. Some authors claim that 3D products remain of limited and simple variety (Gress & Kalafsky, 2015) and that extreme demands are not met (Fawcett & Waller, 2014). According to several trade reports, more complex products remain comparatively rare, because the efficiency and added-value of consumer 3D printing is questioned (Mckinnon, 2016).

Prominent characteristics of 3D printing related to user requirements concern the possibility to pursue product customisation and fast response to customer needs as a result of flexibility and adaptability (Bhattacharjya, Tripathi, Taylor, Taylor, & Walters, 2014; Chan & Chan, 2010; Christopher & Ryals, 2014; Janssen, Blankers, Moolenburgh, & Posthumus, 2014; Lopes da Silva & Vicente, 2013). 3D-printed prototypes can help increase user understanding early in innovation process, decreasing time-to-market and risks of non-adoption (Kanto et al., 2014; Romero & Vieira, 2016). Platforms that are able to serve such "mass customisation" could offer personalisation and the ability to deliver to the "long-tail" of consumer needs (Bogers et al., 2016). Moreover, 3D printing makes the role of the consumer more active: they start acting as "prosumers", producing ideas, designs and finished articles (Chen et al., 2015; Rauch, Dallasega, & Matt, 2016). For retailers, this might create challenges and chances: they can provide flexible printing services but they do not have the opportunity to tease consumers to make impulse purchases (Fawcett & Waller, 2014; Janssen et al., 2014).

Most publications concern the impact of 3D printing on the *location* of manufacturing. 3D printing creates the opportunity to move from mass production to mass customisation to personalisation and distributed production (Bhattacharjya et al., 2014; Mourtzis & Doukas, 2013). This development is associated with two extreme scenarios: centralised versus decentralised manufacturing (Li, Jia, Cheng, & Hu, 2016). Most publications envisage that 3D printing means a more decentralised manufacturing, offering greater proximity to customers and responsiveness to market needs (Fornasiero, Chiodi, Carpanzano, & Carneiro, 2010; Manners-Bell & Lyon, 2012), possibilities to cut out middlemen (Jia, Wang, Mustafee, & Hao, 2016), and even a "de-globalisation" or reshoring of manufacturing to high-income countries (Campbell, Williams, Ivanova, & Garrett, 2011). This is driven by the fact that designs can travel digitally across the globe (Janssen et al., 2014) and may even replace movement of products (Garrett, 2014). The precise locations of the 3D printers can vary, ranging from "print shops" on different continents, city- or neighbourhood-level hubs or "mini-factories" at local service providers such as libraries, community centres and post offices), to printers located at consumers' homes (PWC, 2014; Rauch et al., 2016; United States Postal Service Office of Inspector General, 2014). Production sites that are flexible, lean, agile and responsive are likely to perform well (Barz et al., 2016; Bogers et al., 2016; Jonsson & Holmström, 2016).

At the same time, some authors have reservations about decentralisation. High-volume, low-added-value production will remain more efficient in centralised factories (Holmström et al., 2010; Li et al., 2016; Ye, 2015). The same goes for low-volume and high-added-value manufacturing because of the presence of support infrastructure and specialised human resources (Gress & Kalafsky, 2015). Economies of scale play a role, but there are other characteristics that add to explaining the need for (de)centralisation. They relate to the abovementioned user requirements and include flexibility, adaptability, demand uncertainty, supply uncertainty, and capacity utilisation. There are quite a few publications that address these variables in relation with spare part management, e.g. in the field of aircraft maintenance. There, parts that are not used very often (i.e. "slow-moving parts") still need to be in storage because of a need for fast-repair services. Additive manufacturing may be a solution but still storage, manufacturing and location need to be carefully balanced (Fawcett & Waller, 2014; Holmström et al., 2010; Huang, Liu, Mokasdar, & Hou, 2013).

In terms of *transport flows*, a lot depends on how the location of 3D printing is organised. Most reviewed publications emphasise that 3D printing concerns production closer to home, leading to a decrease in inventories and in distribution between manufacturing and end users (Janssen et al., 2014; Tuck et al., 2007). Despite this forecasted reduction in shipping and air cargo volumes (Barz et al., 2016; Manners-Bell & Lyon, 2012), there will be a shift from manufacturer–consumer distribution to the raw material supplier–manufacturer side. Raw materials are still needed as inputs to the production process, even if manufacturing is decentralised (Gress & Kalafsky, 2015; United States Postal Service Office of Inspector General, 2014). They can be delivered in bulk, with minimal packaging and without urgency, leading to less tonne-km and cubic metre-km of freight movements (Mckinnon, 2016). The decrease holds for 3D printing at home. Locating 3D printers at "mini-factories" might create a different picture, since this might spur short-distance express delivery between these factories and homes (Mohr & Khan, 2015).

3.2. Policy relevant impacts

It is surprising that in terms of transport-related *environmental impact* only a few publications make tentative predictions that emissions and oil use will be reduced (Bhattacharjya et al., 2014; Ford & Despeisse, 2016), despite the fact that many publications report on the impact of 3D printing on goods flows and logistics. There are some hypotheses, such as that long-distance transport could be reduced, and if the last-mile is done by low-emission vehicles, could lead to less emissions (Chen et al., 2015; Rauch et al., 2016). A few authors mentioned that 3D printing is about layer-by-layer production and thus hardly generates process waste in the form of moulds (Barz et al., 2016; Diez, 2012; Garrett, 2014; Lopes da Silva & Vicente, 2013). This is augmented by minimal harmful chemicals needed, possibilities to create environmentally friendly designs, a decrease in excess storage (Campbell et al., 2011), and less weight due to using light materials and due to the possibility to make the interior hollow (Romero & Vieira, 2016). At the same, the process energy consumption exceeds that of casting (Huang et al., 2016) but over a complete life cycle is kept equal (Kreiger, Mulder, Glover, & Pearce, 2014) or lower (Li et al., 2016). Other positive impacts on sustainability include reduced inventory waste due to production-on-demand, and potential for recycling (Despeisse et al., 2016; Ford & Despeisse, 2016).

Concerning *welfare, income and employment*, there are a few publications mentioning the potential disruptive impact of 3D printing on the global transport sector (Bogers et al., 2016). The total system costs may not drop because there will always be a careful balancing between labour costs and transport costs (Chan & Chan, 2010; Manners-Bell & Lyon, 2012). To some, this might lead to a reintroduction of the manufacturing industry to high-income countries, since 3D printer centres can be raised in closer proximity to customers (Frazier, 2014; Janssen et al., 2014), but then favouring high-skilled jobs (PWC, 2014). At the same time, traditional outsourcing countries are increasingly becoming capable to become frontrunners in 3D printing as well (Gress & Kalafsky, 2015).

The reviewed publications did not cover other effects of 3D printing on transport as conceptualised in our a-priori model (Figure 2), such as traffic safety, accessibility and infrastructure needs, nor indirect effects on passenger transport.

4. Towards an a-priori conceptual model

Figure 2 presents the model we designed and adjusted after the first round of expert consultation. In this section, we explain the basis of the model, and the main modifications we made based on the expert consultation.

4.1. Theoretical starting point for the model

Point of departure of the model is that it should conceptualise the dominant policy relevant effects of the transport system: accessibility, the environment and safety. The model is largely based on two other conceptual models, the first one being the transport policy model (TPM; based on Van Wee, 2013). The TPM describes how the transport system influences policy relevant effects: accessibility, the environment and safety. The TPM assumes that environmental and safety effects result firstly from transport volumes (in

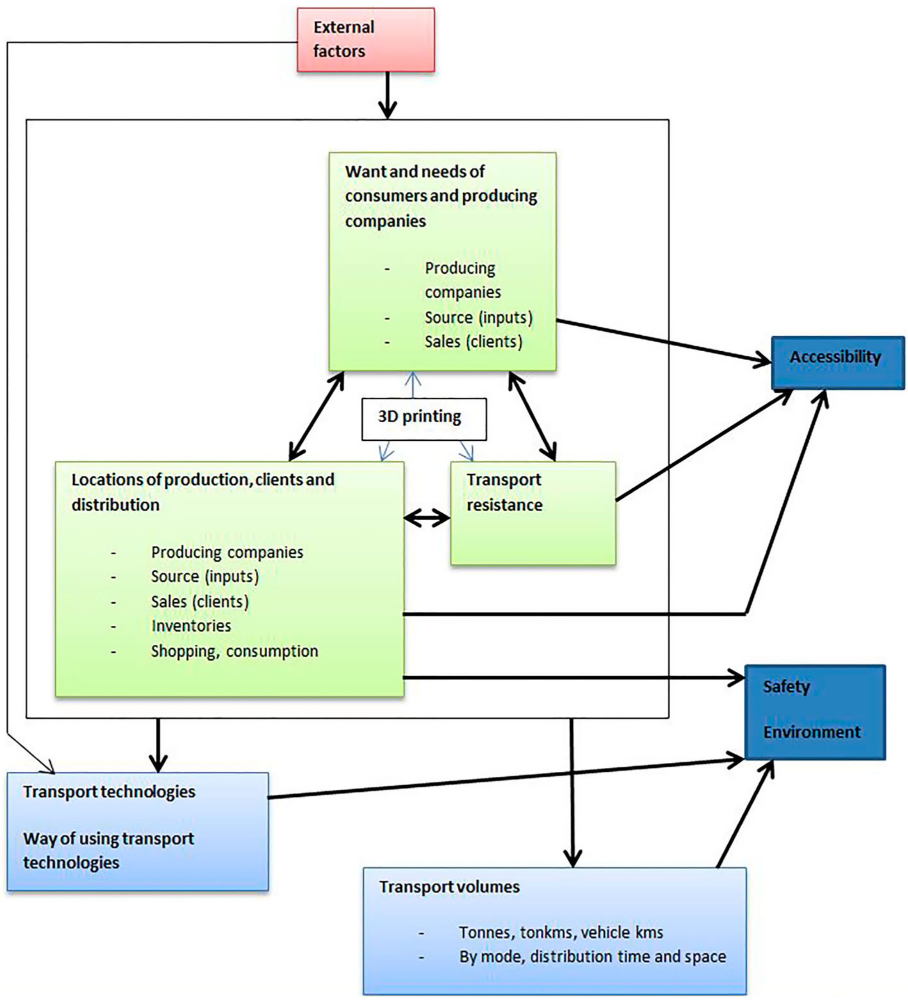

Figure 2. Preliminary conceptual model for the impact of 3D printing on accessibility, the environment and safety.

case of goods transport: measured in tons, ton kilometres and vehicle kilometres) and the distribution of traffic over time and space; and secondly from transport technologies used, and the way in which these are used (e.g. speeds, accelerating and decelerating). Accessibility effects result from the wants and needs of consumers that order and companies that provide transport goods, the locations between which goods are (potentially) transported, and transport resistance, often expressed in terms of generalised transport costs (GTCs), expressed in terms of monetary costs and time. In addition, many other components contribute to GTC, such as (perceived) safety, damage risks and travel time reliability/predictability. GTC depends, amongst others, on infrastructure networks and characteristics, travel speeds and reliability, and available means of transport and their characteristics. Our model departs from the TPM model.

The TPM model was enriched with a second model: the so-called SPITS model describing how Sources, Production, Inventories, Transport and Sales interact (Kuijpers, van

Rooden, van de Ven, & Wierikx, 1995). The model departs from the notion that Production, Inventories and Transport (PIT) mutually influence each other. For example, if production cost differences exceed transport costs, some stages of production will be relocated to low-cost production locations. If inventory costs are very high, such as in some Japanese cities, inventories will be relatively small, but deliveries will be relatively frequent, resulting in higher transport costs than in case of larger inventory facilities. The equilibrium of choices made related to production, inventories and transport depends on characteristics of inputs (Source) and output (Sales). The source side includes factors such as availability, prices and locations of raw materials, energy and other inputs, and labour and capital availability and costs. The sales side involves locations, characteristics and wishes of clients and markets. Recent underpinnings for several components of the model can be found in mainstream goods transport modelling literature (e.g. Tavasszy & de Jong, 2013). The transport component of the SPITS model is equivalent to the resistance component of the TPM model. The Inventories, Production, Source and Sales components of the SPITS model are included in the Wants and needs, and Location boxes (components) of the TPM model.

4.2. Adjusting the model following the literature review and results from the first round of expert consultation

The model presented in Figure 2 allows us to conceptualise potential effects of 3D printing. A first effect of 3D printing is that both *locations* of (a) production, (b) inputs and (c) sales will change. As the literature review revealed, there are different possible scenarios that stress different locations for 3D printing: emphasising printing at home, in neighbourhood hubs, city-scale hubs or continental hubs. As one expert put it:

> 3D printing may be at home or close to consumer locations in fabshops, but not necessarily, given their setup costs. New flows are inbound and outbound of printing and these will replace existing flows. Inbound, raw materials (powders and gels) will require new distribution systems from bulk to consumer portions. Outbound, one can expect that some forms of printing will serve consumers globally. This will scatter B2C flows as compared to current mass production.

From this feedback and the literature overview, we gather that the options for different locations for 3D printing as mentioned above may compete to some extent, but can also be complementary. Hybrid scenarios for different locations of 3D printing seem plausible. It is possible that more advanced 3D printing will (mainly) be done at centres, and that simpler printing will be done at home, and that distinct persons and households make different choices. Some may buy a more advanced 3D printer, others a simpler version. In general, production of goods will concentrate more on mining and farming, and producing the inputs for 3D printers; final products will increasingly become 3D printed. One expert predicted more internet-based sales and inventories for inputs and sourcing becoming more local. This would increase the importance of local transport networks and decrease the importance of long-distance transport. Such change may affect ports and distribution centres.

Secondly, the *wants and needs* of companies and consumers regarding transportation options and location choices depend on e.g. income, time, changing preferences and technological possibilities, of which 3D printing is one. Developing and selling the printer software will become a major economic activity, as will selling the inputs for printers (food and non-food components, in a variety of qualities and "flavours"), and printers. One of the experts said that inventories will to a lesser extent store final products, but increasingly the inputs for 3D printers. The wants and needs of consumers may change, for example because products become cheaper, and designing one's own, tailor-made products becomes possible. "Mass-individualisation may become more important: customer-specific products can easily be designed and 3D printed, and it is possible that consumer behaviour for products will change accordingly". For example, people might more frequently design and print clothes, and recycle old cloths.

Thirdly, we discuss the impact on *transport resistance*. We define transport resistance as the sum of all "cost factors": monetary costs, travel time, (un)reliability of travel times and travel effort (such as safety-related factors and the stress of driving). The impact on transport resistance on rail transport, barge and international shipping will probably be limited because there generally are no major difficulties to solve capacity problems in related transport networks. But, there very likely will be major effects on road freight. On the one hand, goods transport can be organised more efficiently because production chains will become simpler, resulting in less medium- to long-distance road freight. On the other hand, local transport to locations of 3D printing will become more important (the "last mile"). Probably, there will be distribution facilities at the urban or regional scale, from where deliveries to final customers will take place. All in all, impact on transport costs is uncertain: they might become lower or higher, depending on how difficult it is to move raw materials. This might lead to indirect effects. Based on the theory of constant travel time budgets, consumers might shift from spending time on travel for shopping to travelling more for other activities (Mokhtarian & Chen, 2004).

Transport technologies might change due to the complex interactions of the wants and needs of companies and consumers, locations and transport resistance. For example, it is possible that the transport of goods via containers will become less important, and the transport of bulk inputs for 3D printers will become more important, stimulating the development of dedicated transport technologies. Alternatively, powders might become important and transported in medium-to-large quantities, which makes container transport more attractive.

The *time* of day of deliveries might change as far as deliveries to consumers are concerned: this on the one hand may lead to more deliveries outside the office hours, but on the other hand new ways of dispatching might emerge as well, e.g. through smart letterboxes or central courier services.

The experts expect a decrease in *CO_2 emissions* of all freight transport due to the increased efficiency of transport, only if main deliveries are not to consumers but to neighbourhood 3D printing locations or when the last mile is performed by low-emission vehicles. Some production might be reallocated from low-cost countries to "closer to the consumer", reallocating CO_2 and other emissions of production, and even changing absolute levels of emissions due to a change in production technologies. However, the logistical network might also become less efficient: "a change from standard to individualised, highly responsive logistics services [...] will lead to less sustainable logistics systems" (Tavasszy, Ruijgrok, & Thissen, 2003).

There are also *context factors* that can be distinguished. One trend can be that a design industry will emerge, developing and selling the data needed for 3D printing. There may be interactions with other emerging technologies like electric or self-driving vehicles and drones. The role of and interactions between stakeholders may change. For example, politicians may decide upon changes in transport networks, as a result of changing demands for infrastructure. Or they may develop policies to reduce waste flows, and recycle products at a local or regional level.

In sum, the most important changes in the a-priori model made due to the first-round consultation are:

- Transport resistance is defined more explicitly.
- The boxes "wants and needs" and "locations" are made clearer, as well as their descriptions.
- Changing in consumers' wants and needs is described.
- We added the impact on the balance between traditional and internet sales.

The constructed model is presented in Figure 2.

4.3. Results from the second round of expert consultation

In general, the respondents emphasised that they found the presented model clear and consisting of the most relevant elements (8 out of 10 respondents; 8/10). The critical remarks they made about the model were about the unclear operationalisation of the environmental impact and the presence of traffic safety, accessibility and technological developments. The experts found it difficult to assess these variables and questioned whether they were really impacted by 3D printing. So, they stated that the model served its purpose: investigating the impact of 3D printing on transport.

Apart from providing feedback on the model, the experts gave their opinion on (the influence of) every variable. We present these findings, following the blocks of the conceptual model.

Regarding the *location* of 3D printing the experts envisage a 3D printing model in which production happens in city-level hubs (4/10) or in combinations of city-level hubs and home-based printers (4/10). Coordination in a hub is deemed important because of technical complexity, specific knowledge needed, and handling of materials and waste flows. Sourcing will become more local, increasing the importance of local transport networks (9/10). Although long-distance transport might become less important due to reshoring and recycling, pre-processed raw materials still need to be transported from raw material-producing countries. Inventories of local logistical hubs will to a lesser extent store final products, but increasingly the inputs for 3D printers (9/10). Again, the hub level is favoured 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. A comparison is made with 2D printing of photos, books and other publications: consumers can do this at home but professional printing hubs have scale advantage, expertise and more advanced technology. So, the experts were not straightforward about whether 3D printing will change the way in which location decisions are made. Some experts agreed, emphasising near-source production, more flexible and distributed location choice, enabling postponed manufacturing (5/10). Others disagreed, seeing location decision still dependent on a trade-off between transport cost, local labour costs and taxation (3/10). Companies will vary in the business models they adopt, but experts expect the hub model to be favoured over competing approaches and to emerge as the dominant business model.

In terms of consumer *wants and needs*, the experts were quite in agreement. They strongly articulated that mass-individualisation becomes more important and that 3D printing plays a significant part in customer-specific design and manufacturing (10/10). There will be repercussions for the frequency of buying goods by consumers, although some experts say that this frequency will go up (trendy, customised products are disposed more quickly; additions are replaced easier) whereas others claim it will decline (customised products do not need to be replaced). There is less agreement about whether products delivered to consumers' homes will change from final products to raw materials, such as powders and gels (3/10). Again, the notion of printing hubs was mentioned. 3D printing may happen at hub level because customers treat 3D printing as a service, and companies will offer this in a professionalised manner. Consumers do not want their homes to become factories. The experts were also undecided about whether 3D printing will change the type of goods consumers buy: some dedicated 3D-printed products are already available (3/10), but some experts state that 3D printing is only a production method and will not lead to new types of products or needs (4/10).

The experts more or less agreed with each other that 3D printing will change *transport resistance* in a positive way (7/10), especially for products that require customisation. Distribution networks will be organised more efficiently: more nodes, 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. Still, there were dissenting voices amongst the experts who claimed that transportation costs may increase (3/10). Raw materials will need to be shipped and return flows are potentially still low; and the main changes are to occur in the last mile that are associated with more flexibility and higher costs. Also, transport resistance depends on the scalability of 3D printing processes and their efficiency. Costs of handling and coordinating/sourcing/stocking components may decrease, but this is merely an assumption. Moreover, 3D printing may induce demand for raw material like the need for paper increased in case of 2D printing.

To conclude on these three building blocks of the model, we asked the experts which block would have the most influence on 3D printing. Wants and needs of consumers clearly ended on top (5/10), followed by transport resistance (3/10) and location decisions (1/10).

In terms of impacts 3D printing might have, we first asked the experts about the impact on *transport volumes*. Due to 3D printing, transport of goods via containers will become less important, and the transport of bulk inputs for 3D printers will become more important (6/10). One qualification was made that bulk is increasingly transported with containers, and raw materials for 3D printers may require e.g. packaged cartridges. Experts are undecided about the *time* of day deliveries to consumers are made. The answers to repercussions for total transport volumes in tons and in tonkms led to a scattered array of answers ranging from large positive impacts to large negative impact. The majority of experts answered either moderate/no impact (4/10) or "I dont know" (2/10). Reasons for a decrease included extended product-life-in-use, less air to be transported, and reduced number of kilometres in the last mile. Reasons for an increase in transport volumes concern that there is more material that needs to be cut out, and subsequently returned. “No change” arguments focus on the amount of molecules remaining the same.

The impact of 3D printing on *CO_2 emissions* shows the same wide range of answers. Reasons provided include more last-mile kilometres (leading to an increase in CO_2 emissions; 3/10), the same amount of molecules needs to transported (indicating no change in CO_2 emissions; 2/10), and less urgency and less need for just-in-time inventories (decrease in CO_2 emissions; 3/10). Experts were not convinced that 3D printing will impact *traffic safety* and *accessibility*. Most of them (8/10) did not see the relationship and could not think of reasons why the number of traffic or road freight-related victims would change.

Transport technologies are not likely to change because of increased 3D printing practices (6/10). 3D printing is an improvement in manufacturing technology, having limited influence on transport technology. Other influences on transport technology are stronger anyway, such as the need for zero-emission vehicles and alternative powertrains. The only positive examples of new 3D printing-induced transport technologies mentioned are impact through extending life cycles of products and making products on the way.

Lastly, we asked what possible *external factors* would be working on the 3D printing model. First, economic and societal developments were mentioned, such as global GDP and consumption growth. Second, socio-technical developments with regard to 3D printing came up. For example, which additive manufacturing methods will be the prominent way of printing? And which market organisation will become dominant: who makes the deliveries, who creates print-files or makes designs available?

5. Discussion and conclusions

Current literature on 3D printing and transport studies does not provide a systematic model of the impact of 3D printing on transport and related (policy relevant) areas such as traffic safety, location decisions, accessibility, environmental effects, infrastructure needs, welfare, income, employment, consumption patterns and satisfaction (Frazier, 2014).

This paper aims to explore the impact of 3D printing on transport and transport-related impacts on society, including CO_2 emissions, traffic-related safety victims and accessibility. To do so, we develop an initial conceptual model consisting of “wants and needs of consumers”, “location decisions” and “transport resistance”, and their impacts on transport technologies, transport volumes, safety, the environment and accessibility. We based the model on a literature review and refined the model through two rounds of consulting experts. As our consultation was not aimed at generalisability and sample sizes remained small, our results are explorative. Table 2 succinctly summarises the results. We mention when the experts or literature were not agreeing.

First of all, the experts in the second round indicated that the conceptual model contains the relevant and important elements for assessing the impact of 3D printing on transport and transport-related challenges. They were critical about the relevance of including “Impact on time of delivery”, “Development of transport technologies” and “Impacts on traffic safety”.

Table 2. Summary of the articulated variables in the model over the course of the research.

	Literature review	First expert round	Second expert round
Location decision	Decentralisation, but depending on volume, added-value, flexibility, demand/supply uncertainty	Decentralisation, but there is an array of possible forms of 3D printing locations (home-based, neighbourhood-level, hybrid forms)	City-level hubs most likely because they can coordinate material flows and have expertise
Wants and needs	Flexibility and adaptability, but probably of limited and simple variety	Mass-individualisation becomes more important	Mass-individualisation becomes more important; influence on buying frequency (which way is undecided)
Transport resistance	Reduction in shipping but raw materials still needed	Goods transport more efficiently organised as production chains become simpler. Change in transport costs uncertain	Distribution networks will be organised more efficiently, less empty vehicles; but raw materials still need shipping
Impact on time of delivery	Not mentioned	New ways of delivery will emerge	No real influence (other developments have more impact)
Development of transport technologies	Not mentioned	Dedicated transport technology needed, containers less important	No real influence (other developments have more impact)
Impacts on transport volumes	Not mentioned	Not mentioned	Diverging opinions: either increase or decrease
Impacts on the environment	Not mentioned	Slightly positive	Diverging opinions: either increase or decrease
Impacts on traffic safety	Not mentioned	Not mentioned	No influence due to 3D printing
External impacts	Not mentioned	Policy changes on transport networks, recycling, waste flows	Economic growth; 3D printing technological developments; 3D printing market developments

For the specific elements of the conceptual model, Table 2 shows that the literature review and the consultation rounds did not gather many insights into the impact 3D printing might have on the environment, traffic safety, transport technologies, etc. The research does delve deeper into the three building blocks of the 3D printing transport system, i.e. location decisions, wants and needs and transport resistance, though. The experts seem to point to a future in which 3D printing is mainly done in city-level hubs where sufficient coordinating and printing expertise and material flows are present to offer a good-quality service. Depending on volumes, complexity and added-value, there might be deviations to this model, e.g. simpler products can be manufactured on home printers. In terms of consumer needs, an increased significance of individually customised goods is foreseen. At the same time, individualisation will be pursued against the backdrop of economies of scale and product quality being important. Transport resistance changes are likely to be mainly related to monetary costs, and seems to have two sides: more efficient long-distance logistics, e.g. transporting raw materials in cartridges, and a local transport network that might become more efficient (less air travelled, longer life cycle times) or not (more waste that needs to be returned).

The model also provides ideas about future business models in the 3D printing ecosystem. The organisation of operations in 3D printing firms is heavily interlinked with the way in which customer channels are setup, which in turn influences location choice, consumer needs and transport resistance. Two contrasting forces are at work here: 3D printing encourages efficient use and customisation, but also puts pressure on complexity and quality control. Low-quality, low-impact products are obvious candidates for 3D printing closest to home, whereas more complex products could find a place in local print shops.

Will distributed manufacturing then lead to disruption of the logistics market? The presented interlinkages between location choice, consumer needs and transport resistance show that such disruption is not limited to the logistics sector but flows over to manufacturing. As the review above shows, traditional parties who are interested in creating local print hubs include postal services and retailers. They already integrate logistics with managing inventories and sales. Alternatively, as 3D printing supply and demand has a strong digital component (e.g. in sharing designs), coordination may fall into the hands of large IT platform companies like Google or Uber, web-based retailers (such as Amazon) or even globally connected grassroots makerspaces. In conclusion, the model does provide more insights into the influence of 3D printing on location decision, wants and needs and transport resistance, and it provides hints as to how these three aspects are interrelated in the context of 3D printing. The size of impact on transport-related societal issues like transport volumes and the environment is unclear because of contrasting expert answers. The size of impact on traffic safety and technological development in transport is regarded as not existing.

As we emphasised in the Introduction section, this paper fills a gap in the current literature by producing more insights into how 3D printing is influencing transport and related impacts on society. As we described above, the article partially succeeded in this. There are some aspects of the research project that require discussion. First, the model is based on a literature review. The number of previously published papers that touched on 3D printing and transport is not very high, which has the upside that nearly all publications could be included in the review. The downside to this scarcity is that there are aspects to 3D printing and transport that have not been investigated. Second, we used expert opinions in the second and third parts of the project. This has implications for the way in which we can interpret the data. The experts form a sample of knowledgeable people. We did not have the ambition to be generalisable, as our main aim was to explore the model. The way in which we selected the experts to be approached, i.e. focusing on authors of publications, may lead to myopia. On the other hand, the included experts originated from a wide range of organisations and countries. We explicitly left room for the experts to comment and articulate their argumentations. This led to a more informed model, but it also made it impossible for us to quantify the variables and the relations between the variables. A follow-up, larger-scale questionnaire could improve on that. Third, in the last consultation round it became apparent that the model can be disaggregated. Several indicators are required to operationalise impact on accessibility, safety and the environment. Fourth, there is a need to make the model more contextualised: the model could consider types of products, types of supply chains, types of additive manufacturing technologies, city versus rural area, etc. The model could even include competition between types of 3D printing or with other emerging technologies that influence (city-level) logistics and transport such as drones and self-driving cars. All these aspects form a research agenda for investigating the future impact of 3D printing on transport, which can build on the model that we presented here.

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No potential conflict of interest was reported by the authors.

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Appendix: Search strategies for publications

In most of the strategies, we focused on social sciences publications, since search terms such as “transport” would also result in studies on e.g. movement of fluids in the human body. The resulting number of publications ranged from 59 to 474. The authors then scanned the titles and abstracts of these papers to assess the extent to which they are relevant for inclusion in the literature overview. The precision is 2.6–33.9% over the different strategies.

Table A.1. Search strategies for 3D printing in transport (date of search: 10 November 2016).

Search strategy	Search term	Number found	Relevant	Precision
3D print in social sciences	TITLE-ABS-KEY (3d print*) AND SUBJAREA (mult OR arts OR busi OR deci OR econ OR psyc OR soci)	338	37	10.9%
3D print in natural sciences but focused on transport, economics, decision studies, etc.	TITLE-ABS-KEY (3d print*) AND SUBJAREA (mult OR ceng OR CHEM OR comp OR eart OR ener OR engi OR envi OR mate OR math OR phys) AND (LIMIT-TO (SUBJAREA, “BUSI”) OR LIMIT-	474	27	5.7%

(*Continued*)

Table A.1. Continued.

Search strategy	Search term	Number found	Relevant	Precision
	TO (SUBJAREA, "SOCI") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "MULT") OR LIMIT-TO (SUBJAREA, "DECI") OR LIMIT-TO (SUBJAREA, "ECON"))			
3D printing with biomaterials in social sciences	(TITLE-ABS-KEY ("Bioprint*" OR "Prosthetic*" OR "Printed biomaterial" OR "organ-on-a-chip" OR "printed organ" OR "Biofabrication" OR "Tissue print*" OR "3D scaffolds" OR "Tissue engineering" OR "Tissue scaffold*" OR "Regenerative medicine" OR "3d print*") AND TITLE-ABS-KEY (transport OR logistic* OR "supply chain" OR traffic)) AND (LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "MULT") OR LIMIT-TO (SUBJAREA, "SOCI") OR LIMIT-TO (SUBJAREA, "DECI") OR LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "ECON"))	123	18	14.6%
Broader search terms for 3D printing in social sciences	(TITLE-ABS-KEY ("Rapid prototype*" OR "Home fabricat*" OR "distributed manufactur*" OR "Rapid manufactur*" OR "Additive manufactur*" OR "3d print*") AND TITLE-ABS-KEY (transport OR logistic* OR "supply chain" OR traffic)) AND (LIMIT-TO (SUBJAREA, "DECI") OR LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "ECON") OR LIMIT-TO (SUBJAREA, "SOCI") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "ENER"))	112	38	33.9%
Review publications on 3D printing	TITLE-ABS-KEY ("3d print*") AND (LIMIT-TO (DOCTYPE, "re"	274	7	2.6%
Broader search terms for 3D printing in transport-related journals	ALL ("Rapid prototype*" OR "Home fabricat*" OR "distributed manufactur*" OR "Rapid manufactur*" OR "Additive manufactur*" OR "3d print*") AND SRCTITLE (transport* OR logistic*)	59	16	27.1%
Total publications found (with overlap)		1380	127	9.2%
Total publications (without double counting) downloaded		959	93	9.7%
Publications after "snowballing"			12	
Publications after search for "grey literature" on Google and Google Scholar (using 3D printing and transport/logistics as search terms)			6	
Total publications included in literature search			111	