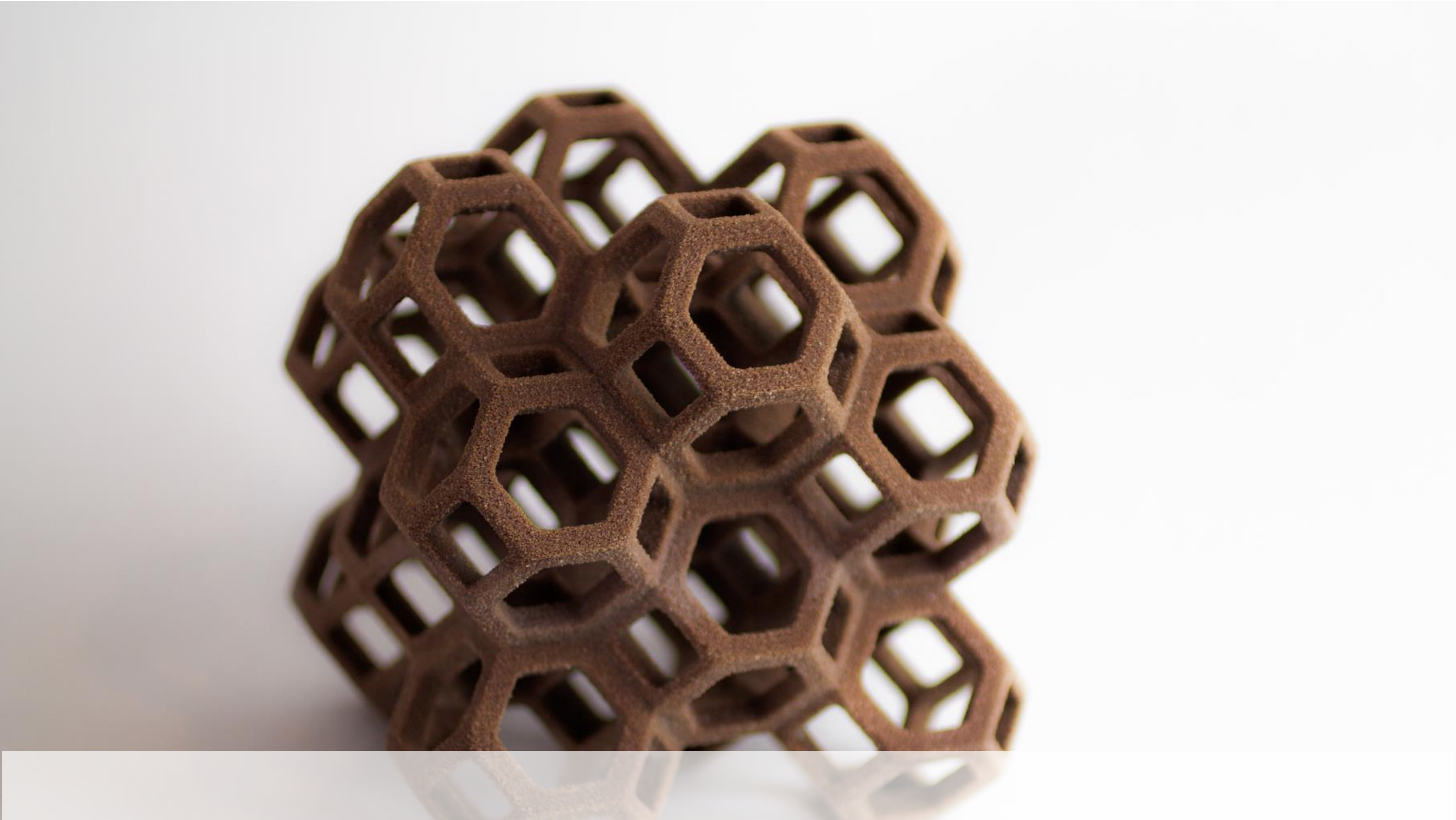

THE IMPACT OF 3D PRINTING ON THE WORLD CONTAINER TRANSPORT

By M. Ye, 2015

Master of Transport, Infrastructure and Logistics
Delft University of Technology

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Preface

My interest for 3D printing technology came about as the result of the media boasting about how it will change the world. At the time I was also in search of a graduation project with subjects regarding freight transport and supply chains. As an amateur stock trader, this propelled me to combine the two subjects to form this project, since I was already interested in analysing the technology for its market potential.

In hindsight, this turned out to be a daunting task, as I often found myself searching for data or links that did not exist, which is extremely demotivating. Due to the, dare I say, “unique” nature of this project compared to the other transport and logistics problems I have encountered during my Masters, it was a real struggle to find related articles. Combined with an episode of personal drama, I was on the brink of quitting.

But luckily, I stuck around. And I couldn’t have done it without the help of various people, whom I’d like to devote this preface to thank. I’d like to thank my supervisors: Ron van Duin, who was always friendly, and quick with replies and providing general advice; Bart Wiegmans, who always made me feel welcome and who greatly helped with the report structure and thus my thinking process; Ronald Halim, who was always generous to provide help even without asking, and provided great practical advice to tackle the simulation model. I’d like to thank my girlfriend Ting, who helped me with the planning which I often struggle with, and for motivating me and giving me confidence. I’d like to thank my roommates at Bagijnhof G, who often offered their help and concerns regarding my graduation, particularly Steven for bring me up to speed with the gravity model. I’d like to thank my friends and family for their moral support. And finally I’d like to thank professor Tavasszy for the opportunity to do this project.

Mao (Mike) Ye

February 2015

Summary

Due to the recent hype around 3D printing technology regarding its disruptiveness for global manufacturing and supply chains, and thus transport in general, an attempt has been made to assess its impact on the global maritime container transport for the next 20 years.

The first step was to gain insight of the 3D printing technology and its sector using literature and market reports. It appears 3DP is still mostly in its infancy. Only basic plastic processes are at the most advanced level. High quality plastic and metal processes are around the pre-production phase, while other material processes are still undergoing experiments. The market and its technical capabilities will surely grow steadily in the next decades. Several improvements can already be expected in terms process improvements, speed, quality control and materials for the coming decade.

The second step involves the assessment of how 3DP relates to current manufacturing and supply chain theories, and to subsequently develop a score model to quantify the current impact of 3DP on manufacturing and supply chains. 3DP provides **manufacturing firms** a unique set of attributes. As firms aim for increasing competitiveness, they will do so by upgrading their competitive capabilities. 3DP influences these capabilities differently (compared to conventional manufacturing) depending on the product that the firm makes and the market in which the firm operates. The 3D Competitiveness Score Model was developed to assess and quantify its competitiveness (or impact) for different markets. It shows to be capable of predicting market potential for a type of product, but not exactly the market penetration. The location of 3DP deployment impacts the **supply chain** and its logistics. The analysis shows that 3DP has been deployed in centralized as well as decentralized manufacturing setups. Case studies of the dental implants and hearing aid industry suggest a high 3DP market penetration also leads to the decentralization (localization) of manufacturing. Market data from the case studies have been used to formulate the relationship between score model scores and the decentralization level, which will be used to derive transport flows.

Due to its extensiveness in terms of variables and statistics used, the World Container Model will form the basis for assessing the future 3DP impact on the world container transport. Five different future scenarios are formed based on varying technological advancement rates of 3DP. Based on the notion that the decentralization level equates to the percentage of transport volume reduction in tons for NSTR 9 commodities (final goods), and allocation of this volume to the supplying NSTR group based on the raw material composition of the NSTR 9 subgroup, the new O/D matrix containing TEUs distribution between countries can be compiled.

The WCM results show that 3DP is not likely to cause a threat, in the form of significant throughput or transport flow reduction, for the global container transport in the next two decades. As the GDP and world population is not likely to decline the next 50 years, the global trade will likely continue to generate a high global transport demand, including container transport. This partly neutralizes the threat of reduction in container transport demand. Any reduction will be masked by the stronger growth of container transport activity. The Port of Rotterdam will remain among the top 11 of the largest ports in the world in terms of container throughput. As a major port, the change of container flow in several links caused by 3DP is likely compensated by an increase of transport flow on other links, and the high global growth of container transport demand.

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Acronyms

3D	Three-dimensional
3DCSM	3D Competitiveness Score Model
3DP	3D printing
AM	Additive manufacturing
CAD	Computer Aided Design
CADCAM	Computer Aided Design, Computer Aided Manufacturing
CM	Centralized manufacturing
DM	Decentralized manufacturing (or Distributed manufacturing)
GDP	Gross Domestic Product
GII	Global Innovation Index
NSTR	Nomenclature uniforme des marchandises pour les Statistiques de Transport, Revisée
OEM	Original equipment manufacturer
SC	Supply chain
Sc.	Scenario
TEU	Twenty-foot equivalent unit (container)
VOT	Value of Time
WCM	World Container Model

Illustration 2

Illustration by Brett Ryder in the article "The third industrial revolution", in The Economist (2012)

Illustration 2

A 3D printed representation of Brett Ryder's illustration for the Third Industrial Revolution article (XYZWorkshop, n.d.)

Chapter 1

Introduction

"The first industrial revolution began in Britain in the late 18th century with the mechanisation of the textile industry… The second began in America in the early 20th century with the assembly line, which ushered in the era of mass production. As manufacturing goes digital, a third great change is now gathering pace."

Paul Markillie (2012), editor for The Economist

3D printing technology is considered by some to bring the "third industrial revolution" (Markillie, 2012; Wohlers Associates, Inc., 2011; Anderson, 2012; Yagnik, 2011) and the "end of globalized supply chain" (Copeland, 2012; Thymianidis, Achillas, Tzetzis, & Iakovou, 2012). This technology, also referred to as "additive manufacturing", is an automated production technique in which a product is build up layer by layer (an additive process) using a computer aided design (e.g. CAD drawing). Today's 3D printers are already quite advanced. Reportedly they now are able to print end products with multiple materials, such as a hammer (Markillie, 2012), or products with moving parts without the need for assembly (Manners-Bell & Lyon, 2012). The implications of 3D printing technology are becoming widespread and vary among products and industries. How this technology relates to transport and logistics, the research question that follows (Section 1.1), the contribution (Section 1.2), the scope (Section 1.3), and the research approach (Section 1.4) will be discussed in the this chapter.

1.1 Research question

In essence 3D printing technology follows exactly the opposite model of the conventional manufacturing method: mass production. With this technology, manufacturers are able to make a single unit of a product at a fairly low cost. As the production time and unit price will decrease over time with technological progress, so will the total cost of locally manufactured products to the point where they could compete with products that are manufactured abroad. When increasingly more manufacturers decide to 'near-source', it could lead to a shift in the global supply chain or a 'reversal in the globalization process' (Manners-Bell & Lyon, 2012), a scenario in which there is a significantly lower demand for freight transport between the East and the West. Thus 3D printing is believed to be a disruptive technology and a potential threat especially for industries such as logistics and manufacturing.

Most literature acknowledge the possible impact of this technology, however none yet exist that has specified and quantified this impact for the logistic and manufacturing industries. Van Diepen (2011, pp. 28-51) considers 3D printing to be influential for future supply chains and the logistics sector, but without elaboration concludes that it will have a "low probability of actualization" and a "low impact" on the Port of Rotterdam based on unspecified reasons. Manners-Bell and Lyon (2012, pp. 3-5) have formulated numerous implications of 3D printing for the logistics industry, such as that it "would reduce shipping and air cargo volumes" and result in "reducing warehouse requirements", but do not disclose on the quantities nor the timeframe. Hopkinson, Hague and Dickens (2006, pp. 19-172) have evaluated the impact on consumers, businesses and on the design and distribution of products, but also do not provide quantified statements. The most methodological study that has attempted to concretely formulate this threat is possibly 'Rapid Manufacturing and the Global Economy' by Driscoll (2008). In his thesis the author identifies the most likely impacted products, and quantifies those impacts to reflect upon the real impact of 3D printing on major economies. In addition to Driscoll's study, in this paper the goal is to extend his scope by including the implications of 3D printing for the global logistics industry in the next 20 years. The focus will be on the maritime transport network, since it moves the most goods in terms of volume and value, respectively 90% and 73% of global trade (Rodrigue, 2013a). And because 3D printing involves manufactured goods, which generally require containerized transport, the emphasis is on the maritime container transport. The research question can be formulated as follows:

> *What is the impact of 3D printing technology on the international seaborne container flows and major ports in the next 20 years?*

From the research question the following sub research questions can be formulated:

1. *What are the current developments in the 3D printing sector?*
2. *What is the impact of 3D printing technology on manufacturing?*
3. *What is the impact of 3D printing technology on supply chains and logistics?*
4. Considering these factors, what is the impact of 3D printing on the world container transport in the next 20 years?

1.2 Contribution

This thesis contributes with the following utilities:

- A **consolidated theoretical overview** of how 3D printing as a concept relates to current manufacturing and supply chain paradigms. This gives a general scientific understanding of the new technology.
- A **generic score model** based on operations management to assess the market potential of 3D printing for certain products. This could be used as a tool by manufacturing companies to assess the applicability or usefulness of this technology for their business.
- **Insight of supply chain structures** of firms that utilize 3D printing. This can help companies understand and react to the manufacturing and supply chain setups that the new technology is enabling.
- **Forecast of future container transport flows and port throughputs** are generated using a computer simulation model. The results can give the stakeholders (e.g. shipping companies, ports) an idea of how exactly this new technology can impact their business. Also it provides the World Container Model a new layer of depth.

1.3 Scope

While the global impact can be infinitely elaborated, the time constraint limits the amount of detail in this work. Thus a scope must be set:

- The **geographical scope** is global, but with emphases on major ports and trade routes, such as the Port of Rotterdam. Manufacturing and transport is largely a global practice, thus such scale is mostly suitable.
- The considered **mode of transport** is the container transport by sea between ports. The hinterland transport, such as those by truck, rail or barge are not considered.
- The **time horizon** will be 20 year from now, which is 2035. As the horizon increases, the less accurate and relevant the forecast becomes.
- 3D printing concerns manufactured products. The latter are mostly transported using containers. Thus the scope will be limited to **containerized commodities**.
- The assessment will mainly focus on the **developments of 3D printing technology** and its impact. Endogenous developments, such as politics and microeconomic changes of ports, are not considered.
- The scope will be limited to **the biggest stakeholders**, which are the deep sea carriers, major ports and freight owners. These stakeholders have the highest stake in arranging the global transport. Any disruption in the global transport will likely be first registered by them.

1.4 Research approach

This subchapter explains the research approach per sub research question and gives an overview of the thesis structure.

1.4.1 Sub research questions

The main research question has been divided into four sub research questions. This is to reduce the complexity of the main research question by using a stepwise approach. The research method and data sources that are necessary to answer each sub research question are described in this section.

What are the current developments in the 3D printing sector?

The first step is to gain as much insight as possible into the field of 3D printing. This can be done through an extended literature review. The results will provide an overview of industries and sectors where 3D printing technology is currently being used and could be used in the future. It shows the current state of development of the technology and its future potentials. Also it determines and assesses the limitations of the technology. Knowledge gained from answering this sub question will be the foundation for tackling the following sub research questions.

What is the impact of 3D printing technology on manufacturing?

The second sub research question will be answered through a qualitative analysis. The objective isto quantify the impact of 3D printing on a product level so it can be aggregated later to assess the global trade of those products. The analysis framework will be based on the competitive capabilities of manufacturing firms. The notion is that businesses will only deploy a tool, such as a 3D printer, if it will enhance its competitive advantage. In the analysis, a 3D printed variant of a product will be evaluated on its competitiveness compared to the conventionally made product. Market analysis and case studies might be necessary to understand the different markets. Finally a quantifiable score representing the amount of impact can be applied to each product group. The method of evaluating and scoring will resemble a Multi Criteria Decision Analysis.

What is the impact of 3D printing technology on supply chains and logistics?

To answer the third sub research question, a general understanding of current supply chains and logistics is required. The goals is to gain insight of the inner workings of conventional supply chains and compare them with supply chains with 3D printers deployed in order to assess the potential disruption of the technology. This can be achieved through a systems analysis of conventional supply and distribution setups of various industries that are involved today with 3D printing industry. Then a comparison will be made with competing supply chains that deploy 3D printers. Knowledge gained here will be used to answer the last sub research question.

Considering these factors, what is the impact of 3D printing on the container transport in the next 20 years?

The last sub research question will consider all factors derived from the analyses of previous sub questions. Different future scenarios will be used to make a forecast through the World Container Model. This forecast should finally be upheld as a comprehensive answer to the main research question.

1.4.2 Overview research approach

Table 1-1 shows an overview of the research methodology per sub research question and the matching research method and data source.

Table 1-1 Overview research approach

Sub research question	Research method	Data source
1. What are the current developments in the 3D printing sector?	Literature review	News articles, reports, books, journals
2. What is the impact of 3D printing technology on manufacturing?	Literature review, market analysis	News articles, reports, books, journals
3. What is the impact of 3D printing technology on supply chains and logistics?	Systems analysis, case studies	News articles, reports, books, journals
4. Considering these factors, what is the impact on the container transport in the next 20 years?	Forecasting, modelling	World Bank, Eurostat, UNCTAD, Trade statistics

An overview of the chapters is presented, which is derived from the four sub research questions (Figure 1-1). The report will consist of a total of 8 chapters.

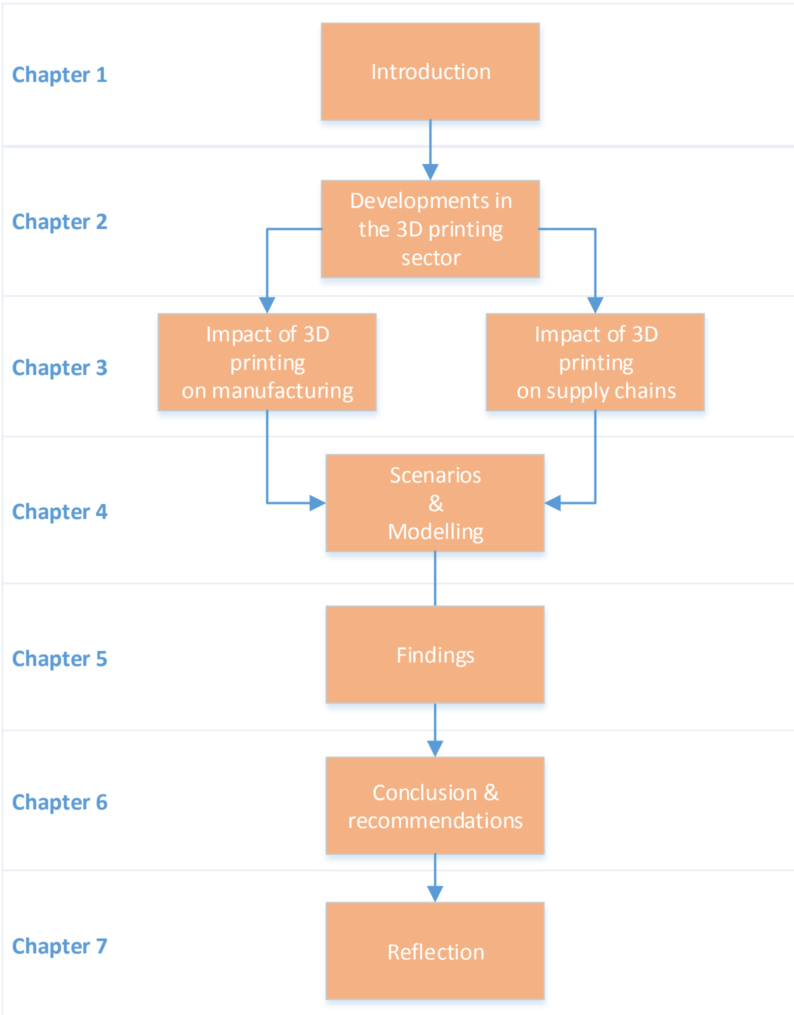


Figure 1-1 Report structure

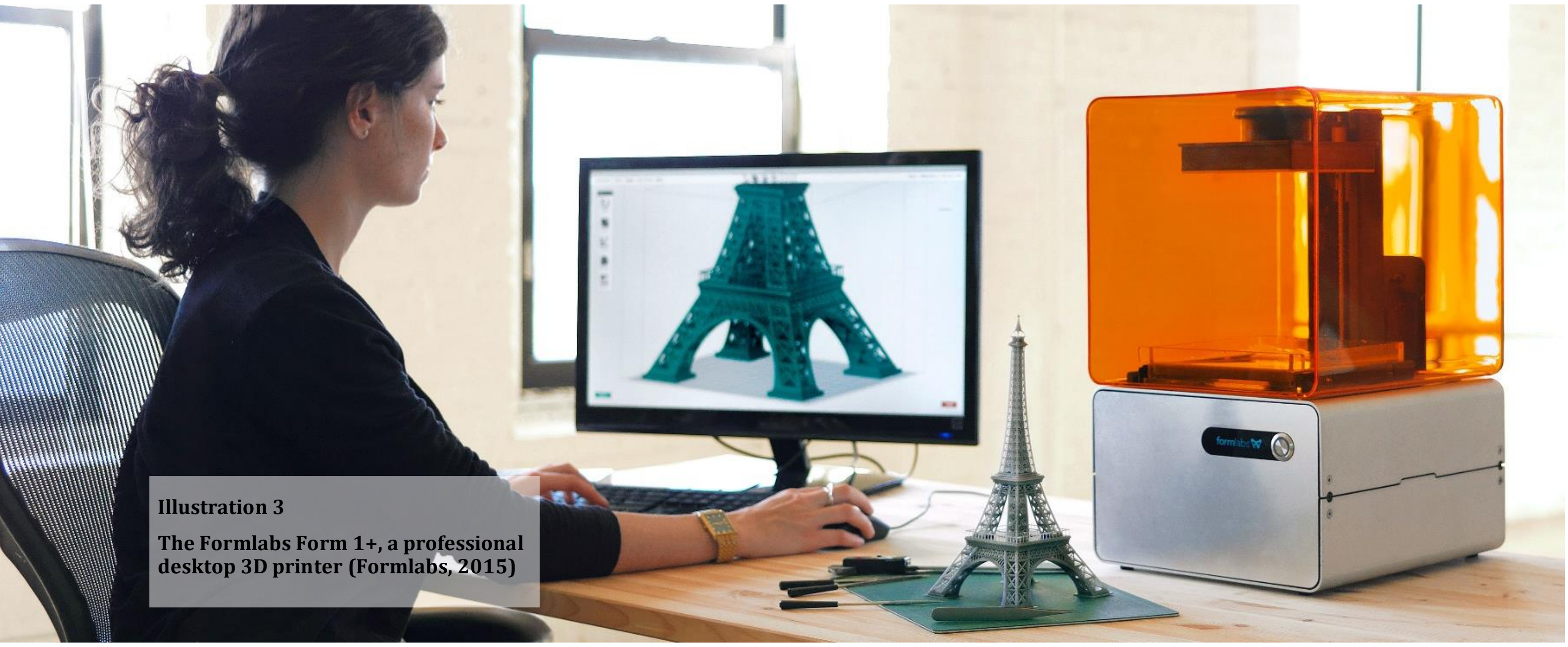


Illustration 3

The Formlabs Form 1+, a professional desktop 3D printer (Formlabs, 2015)

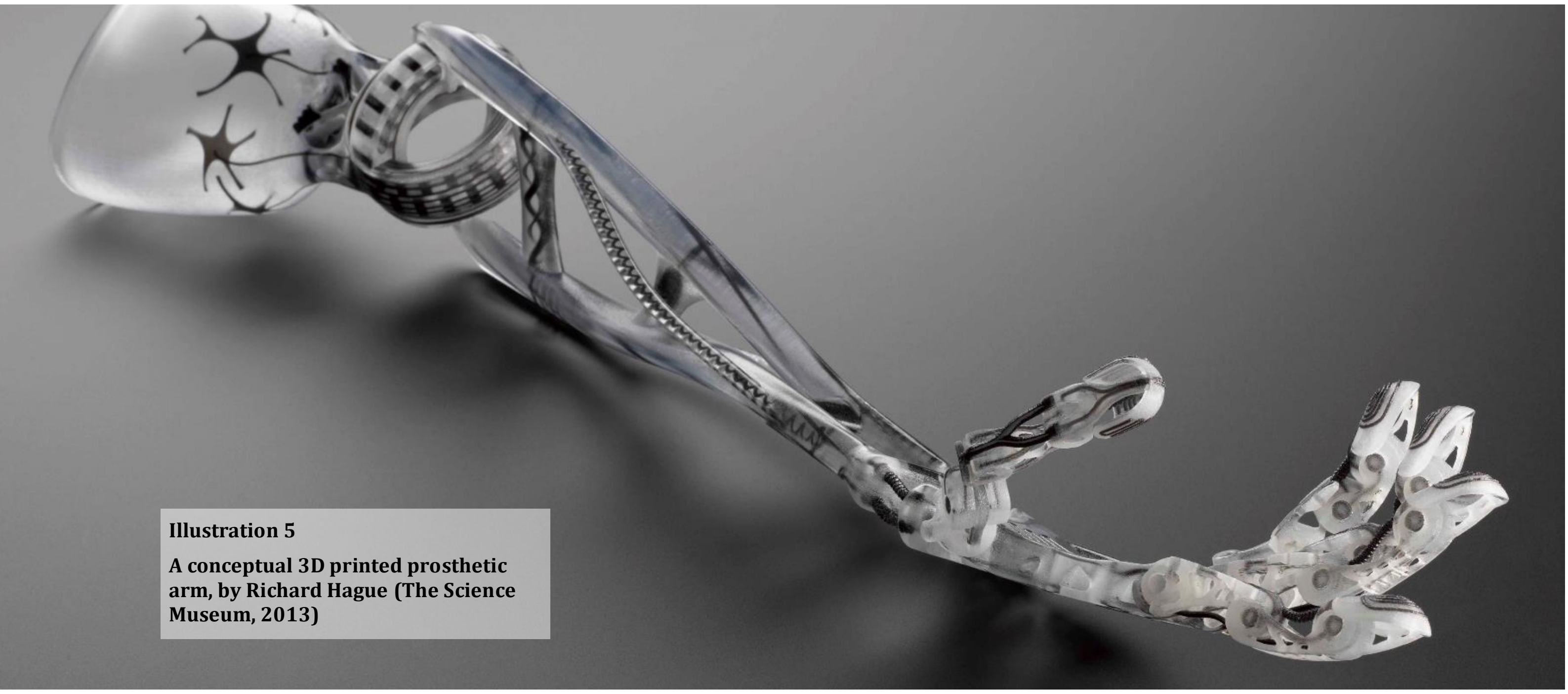


Illustration 5

A conceptual 3D printed prosthetic arm, by Richard Hague (The Science Museum, 2013)

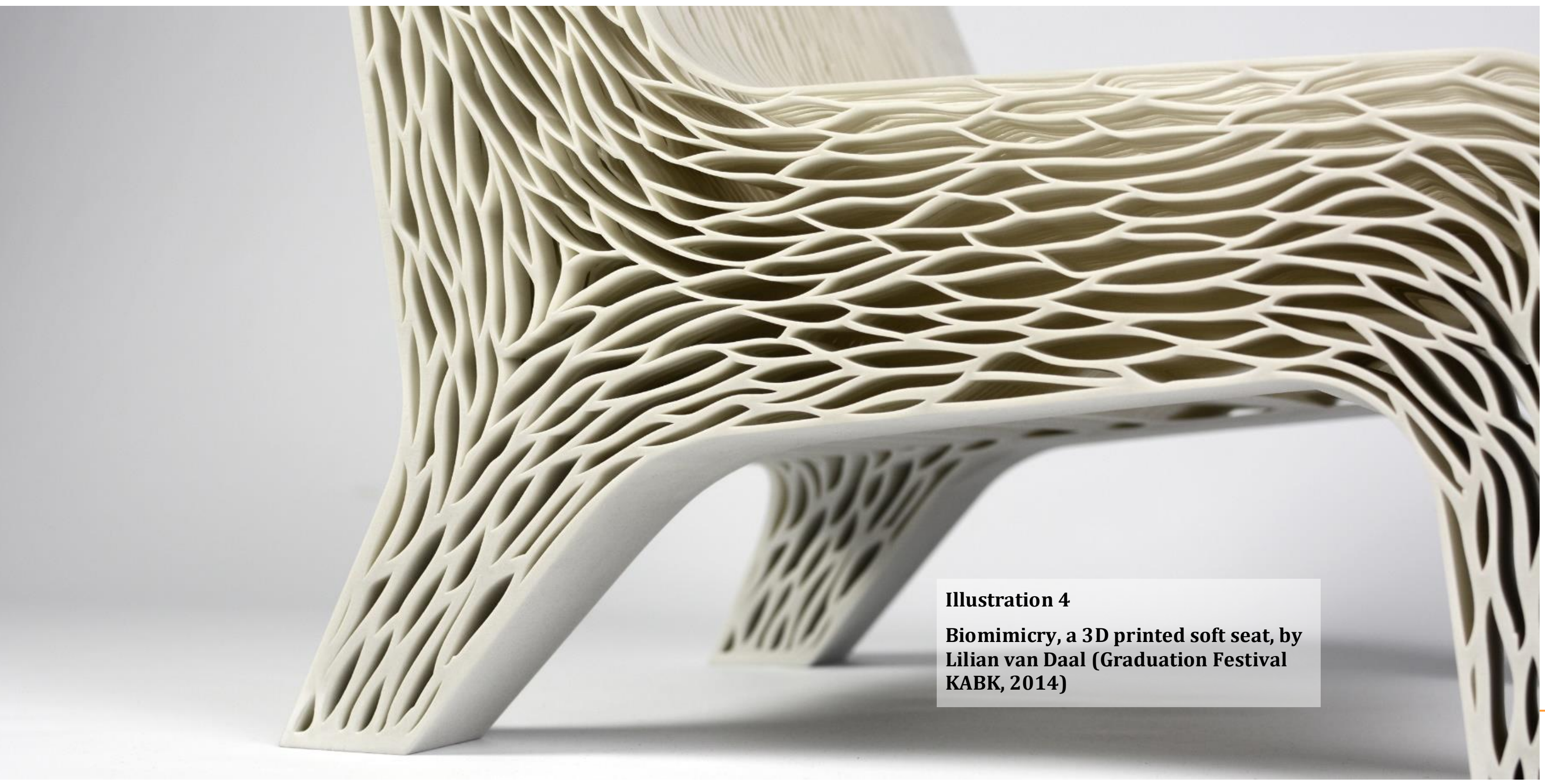


Illustration 4

Biomimicry, a 3D printed soft seat, by Lilian van Daal (Graduation Festival KABK, 2014)

Chapter 2

Developments in the 3D Printing sector

"Tea. Earl Grey. Hot."

Jean-Luc Picard, captain of the
Starship Enterprise

Tea, or any other food could be instantly made on-demand with the "Replicator" in the classic TV series Star Trek. The Replicator was machine capable of using pure energy to create any inorganic matter, as long as the desired molecular structure was known. One can only hope that today's 3D printers may one day become something as advanced as the fictional machine. Likewise, some have compared 3D printers with the sci-fi machine, and written about how 3DP will revolutionize the world and create new business models. But what is 3DP exactly and what is the current status of this technology? The goal of this chapter is to gain a general understanding of the 3D printing technology and its sector today. It explores the history of 3D printing technology (Section 2.1), its current applications (Section 2.2) and the trends (Section 2.3), to help us understand where it came from, its benefits and limitations, and to get an indication of where it is heading.

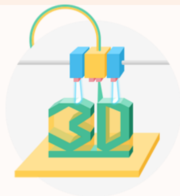
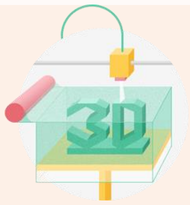
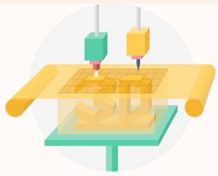
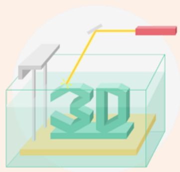
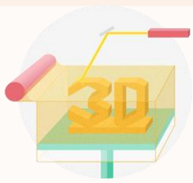
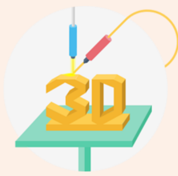
2.1 History of 3D printing technology

In this subchapter we are going to examine what the technology is and where it comes from. Section 2.1.1 gives an overview of the terminology of 3D printing processes and describes them briefly. Section 2.1.1 shows the key milestones in the history of 3D printing.

2.1.1 Terminology of 3D printing and its process classes

There is a **wide variety of processes** in the 3D printing (3DP) industry that several researchers in the past have attempted to categorize (Scott, et al., 2012). As the 3DP technology evolved with new

Table 2-1 3DP processes with utilized materials and explanation (Scott, et al., 2012; Wohlers, 2012c; THRE3D, 2014). A detailed explanation of each process class can be found in Appendix A.

Process class		Materials	Markets
Material Extrusion Material is selectively dispensed through a nozzle or orifice.		- Polymer	- Prototyping
Material Jetting Droplets of build material are selectively deposited.		- Photopolymer - Wax	- Prototyping - Casting patterns
Binder Jetting A liquid bonding agent is selectively deposited to join powder materials.		- Metal - Polymer - Ceramic	- Prototyping - Direct part - Casting moulds
Sheet Lamination Sheets of material are bonded to form an object.		- Hybrids - Metal - Ceramic	- Prototyping - Direct part
Vat Photopolymerization Liquid photopolymer in a vat is selectively cured by light-activated polymerization.		- Photopolymer	- Prototyping
Powder Bed Fusion Thermal energy selectively fuses regions of a powder bed.		- Metal - Polymer - Ceramic	- Prototyping - Direct part
Directed Energy Deposition Focused thermal energy is used to fuse materials by melting as they are being deposited.		- Metal	- Direct part - Repair

processes, so did the terminology. Many terms were used to describe it, such as automated fabrication, digital fabrication, additive fabrication, (solid) free-form fabrication, (direct) digital manufacturing, rapid manufacturing, e-manufacturing, stereolithography, three-dimensional printing, rapid prototyping, or fabbing (Shipp, et al., 2012; Park, Rapid Manufacturing Today, 2006).

3DP technology involves an additive process of creating solid objects layer by layer, hence the technical term "additive manufacturing" (AM); the opposite of conventional, subtractive, production processes where a component is cut out of a lump of material. In 2009, American Society for Testing and Materials International (ASTM committee F42) decided that the standard terminology to describe the entire field will be additive manufacturing (ASTM, 2009). The terms 3DP and AM can be considered synonymous umbrella terms for all 3DP techniques. ASTM has also categorized all the processes into **seven classes** (Table 2-1). The purpose of this **standardisation process** is to stamp out any confusing communication within the industry, "promote knowledge of the industry, help stimulate research and encourage the implementation of technology" (ASTM, 2013; ASTM, 2009).

2.1.2 Key milestones in the 3D printing history

3D printing (3DP) is one of the many technologies that came about as a result of the **invention of the computer**. Early 3DP experiments date back to the 60s (LEF, 2012), but it was not until the associated technologies (Computer-aided design (CAD) software, lasers, controllers) had caught up in the 80s (Gibson, Rosen, & Stucker, 2010), that 3DP could be commercialized. This was accomplished by 3D Systems with its stereolithography apparatus in 1986. A historical timeline is shown in Figure 2-1.

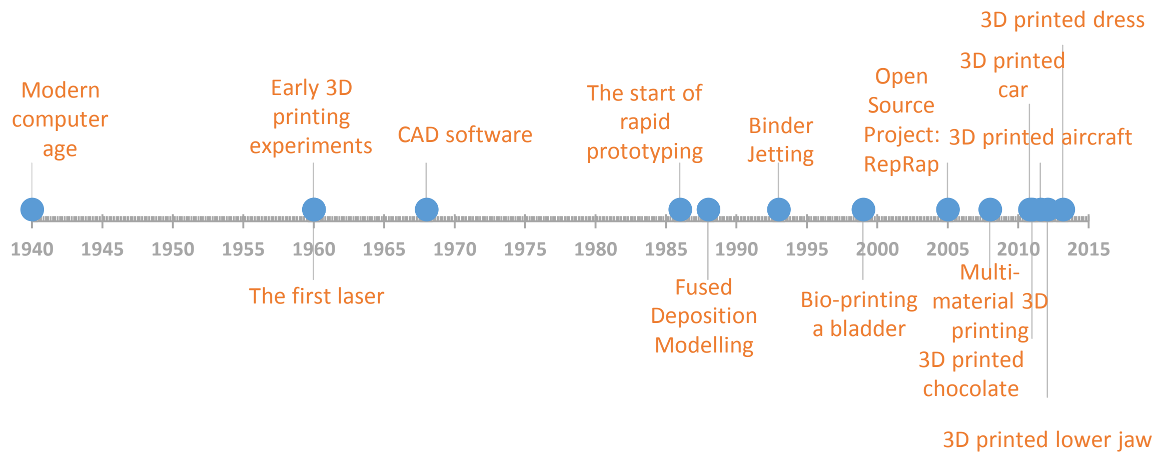


Figure 2-1 Historical timeline of 3D printing technology (Gibson, Rosen, & Stucker, 2010; 3ders.org, 2014; McLellan, 2014)

Development of other technologies around the same time, such as laser-based processes and inkjet head 3DP, have led to further **commercialization in the 90s** (Shipp, et al., 2012; Gibson, Rosen, & Stucker, 2010). As time passes, new processes were invented, existing processes were more refined, new materials were introduced such as ceramics and metals, the technology eventually evolved to a level where the quality of the printed products was high enough for producing of parts for final products, such as chocolate, parts for cars and aircrafts, and prosthetics. Although today most 3DP processes are still used for rapid prototyping (AM SIG, 2012), manufacturers are increasingly deploying the technology for **direct part production** (production of parts for final products).

2.2 Current state of 3D printing

This subchapter explores the current state of the 3DP technology and its sector, by assessing the current maturity of 3DP technology (Section 2.2.1), the largest drivers of the sector (Section 2.2.2), and the barriers that have to be conquered for 3DP to reach further market penetration (Section 2.2.3).

2.2.1 Manufacturing Readiness Level of the 3D printing technology

The maturity of an evolving manufacturing method is usually assessed using the **Manufacturing Readiness Level (MRL)**, which is widely used by government agencies and major firms. MRL basically shows how far a technology is from implementation, as a technology has to go through experimentation, refinement and realistic testing before it is released for adoption. The MRL is divided into 3 phases consisting of 10 levels, with level 1 being the least mature and level 10 the most mature. The different phases and levels are shown in Figure 2-2. The level numbering were designed to be roughly congruent with Technology Readiness Levels (TRL) for ease of use, hence MRL and TRL will be considered equivalent here.

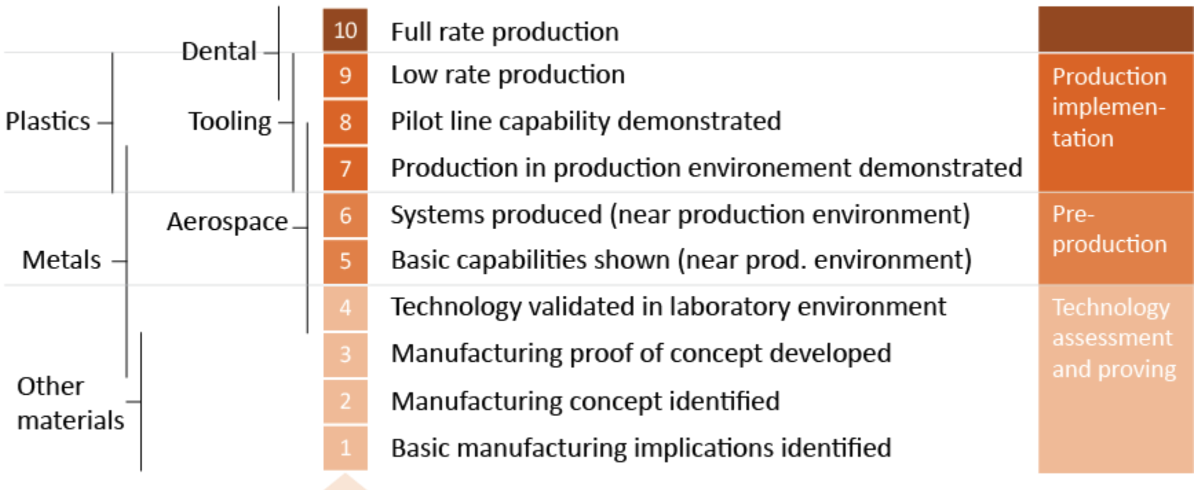


Figure 2-2 Manufacturing Readiness Level, adapted from 3DP Platform (2014) and Roland Berger Strategy Consultants (2013)

3DP applications can be found at all levels on the MRL scale. Many applications have been developed and are **awaiting exploitation for commercial gain**, which is approximately MRL 4. Plastic processes, 3DP processes that involve the deployment of **plastic materials**, are generally at higher levels (MRL 7-9) compared to metal processes (MRL 3-7) (AM Platform, 2014). However, plastic processes with good engineering properties are at lower levels (MRL 4-5). 3DP processes with other materials, such as ceramics, are at the lowest levels (MRL 1-3). The **dental industry** seems to be the furthest in terms of using 3DP for production (MRL 9-10) (Roland Berger Strategy Consultants, 2013), followed by the tool making industry with a MRL between 7 and 9. Aerospace falls between MRL 4 and 8, with the majority of components being considered for aerospace manufacture around MRL 4-6 level (AM Platform, 2014). It is believed that it is particularly difficult for a new technology to move past MRL 4-6, also known as the "valley of death" (AM Platform, 2014). While the feasibility of applications can easily be proven in laboratories, it still **requires a lot more development and investment** in order to achieve process capability and stability in full production.

2.2.2 Largest drivers of the 3D printing sector

3DP has experienced significant advances and today the technology is being used by a **variety of industries**. The three largest contributing industries to the 3DP market are consumer products/electronics (20,3%), automotive (19,5%), medical (15,1%), which are responsible for more than 50% of its revenue. 3DP offer these industries several benefits over conventional production, such as shorter development times, lighter components, easy customization, and more design freedom. Figure 2-3 shows an overview of the 3DP revenue contributed by each sector. The current state and the trend of other contributing industries, and the role that 3DP technology plays within those industries are described more in detail in Appendix B (p73). **Decisive success factors** for reaching a higher level of market penetration in the future are increased surface quality, new materials, and increased reproducibility (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). Other success factors (based on analysis of the fourteen sectors in which 3DP is considered to have potential) are shown in Figure 2-4.

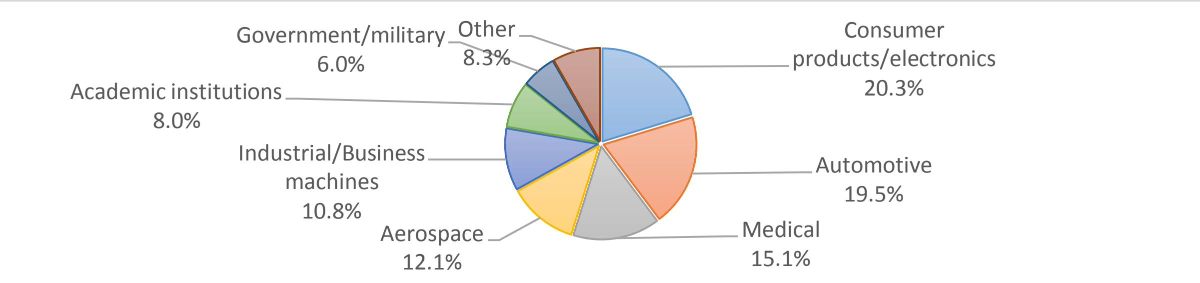


Figure 2-3 3DP market share among different sectors (AM Platform, 2013; Best News, 2013)

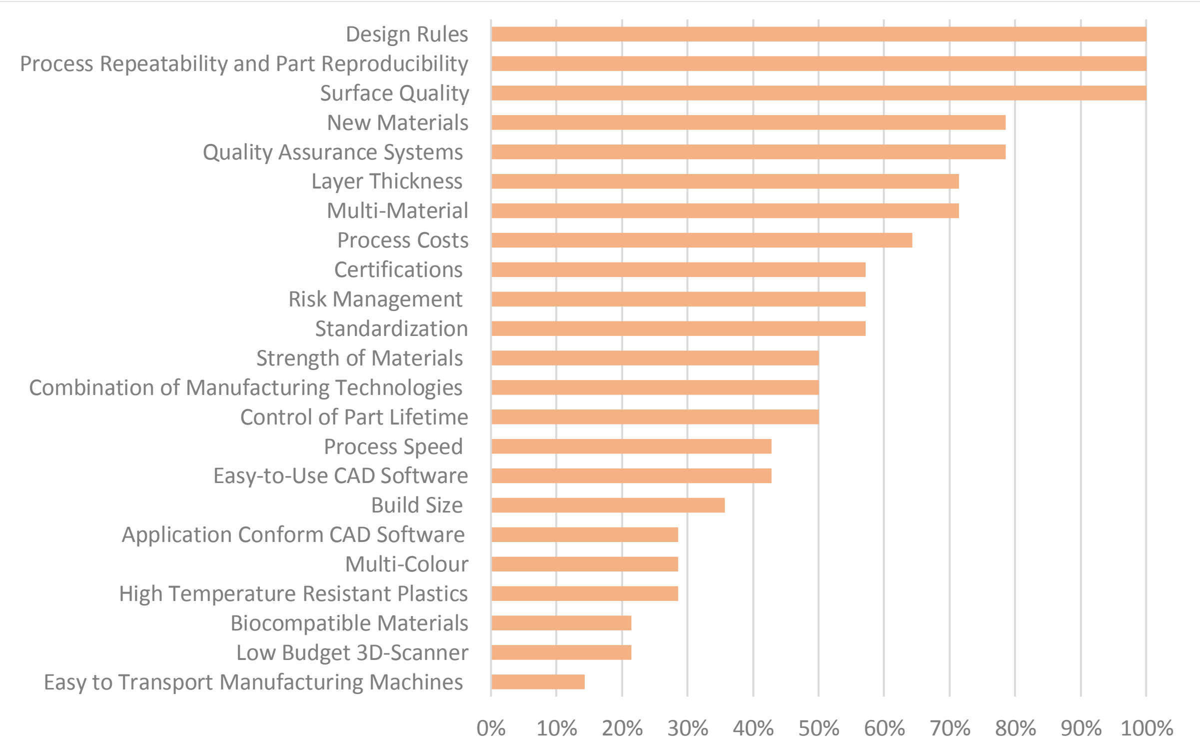


Figure 2-4 Decisive success factors for reaching higher market penetration for various industries, adapted from Gausemeier, Echterhoff, Kokoschka & Wall (2011)

2.2.3 Barriers of the 3D printing sector

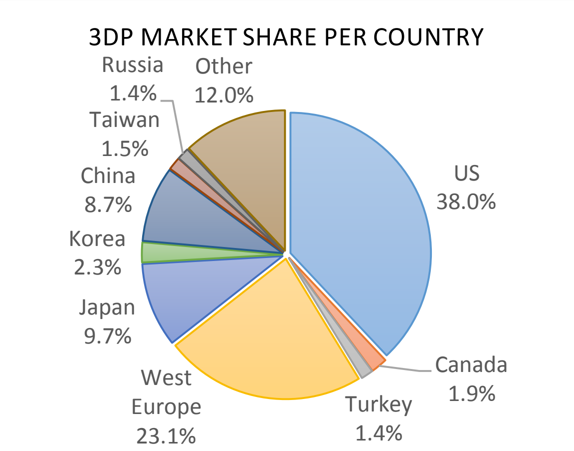
There are various barriers that need to be dealt with for 3DP sector to reach higher market penetration. The commonly described barriers are:

- **Limited robustness of processes.** More control and monitoring methods are required to address the lack of consistency in today's printed batches, especially for safety related components (AM Platform, 2014; AM SIG, 2012). Post processing is often required to meet product specification.
- **Material limitations.** Materials are not always optimized for 3DP processes and are not sufficiently strong or durable (AM SIG, 2012). Also the choice in material is mostly limited to polymers and a few types of metals. New developments in material and material systems are required for increased 3DP adoption (AM Platform, 2014).
- **High component costs.** Due to the slow build speed and expensive materials, 3DP is mainly suitable for small production runs as the cost per part is high. Also the upfront machine investment cost can be a barrier (Shipp, et al., 2012; AM SIG, 2012).
- **Limited access to data.** There is limited access to performance data for 3DP components, materials and processing parameters (AM Platform, 2014; AM SIG, 2012).
- **Intellectual property issues.** Intellectual property theft is made easier as the design files can be easily copied, distributed and pirated, much like in the music and film industry. Also, companies that possess relevant 3DP patents are not motivated to share them, which restricts competition and slows innovation (Shipp, et al., 2012; AM Platform, 2014).

2.3 Trends in the 3D printing sector

In this subchapter, we will explore the current trends in the 3DP market (2.3.1) and the expected technological developments in the near future (2.3.2).

2.3.1 Market trends in the 3D printing sector



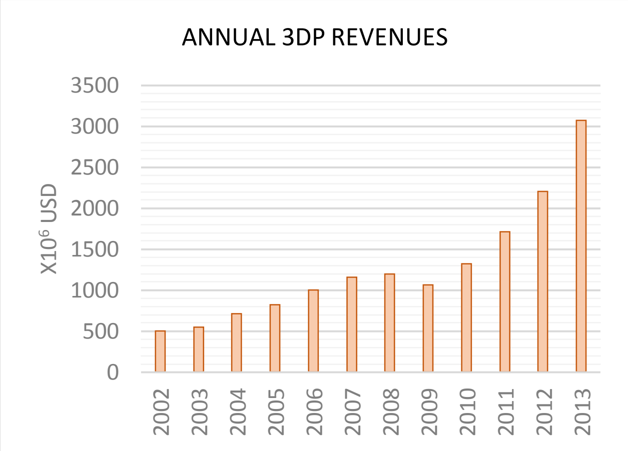
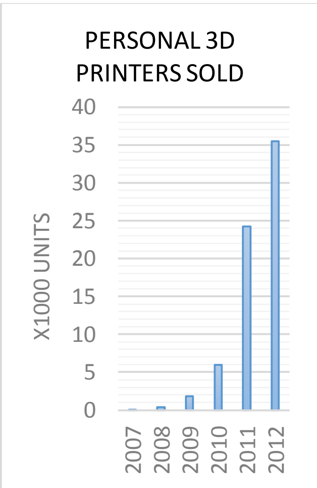
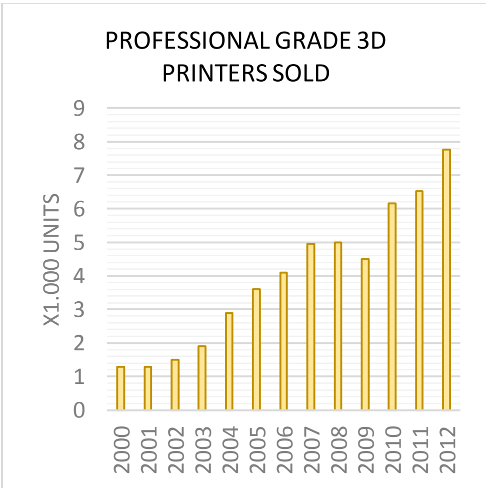


Figure 2-5 (Left) 3DP market share per country (Wohlers, 2013a)
Figure 2-6 (Right) Annual global 3D printing revenues (Wohlers Associates, 2014)

There is a **growing international interest** in using 3DP technology (Scott, et al., 2012). Currently US and Europe are the most developed markets with a total of about 50% of all the industrial 3DP systems installed in the world (Wohlers, 2013a) (Figure 2-5). China and Japan have respectively 8,7% and 9,7%. Countries are interested in further developing the technology. For example Australia's roadmap for 3DP to move down the supply chain in its mining and metals sectors, and South Africa's support for the development of a high speed 3D printer for titanium parts (Scott, et al., 2012). Also the international press has a growing fascination with this technology. 16.000 articles on 3DP were published in 2012 compared to 1.600 in 2011 (Wohlers, 2013a).

The sales of **personal** (<$5.000 per unit) as well as **professional-grade** (>$5.000 per unit) 3D printers are increasing. The sales of personal 3D printers have grown exponentially from 66 units in 2007 to 35.508 units in 2012 (Figure 2-7), mainly due to the price drop to below $2.000 for some models (Scott, et al., 2012). Most of these printers are sold to hobbyists, do-it-yourselfers, students, and educational institutions (Wohlers, 2013a). The sales volume is also rising for professional-grade printers, which amounted to 7.771 units in 2012 (Figure 2-8). While five times more personal 3D printers were sold, the majority (99%) of the revenue came from professional grade 3D printer sales (Wohlers, 2012c). Also the use of **3DP for production of final products has grown significantly** the past 10 years. While only 4% of the total product and service revenues came from direct part production in 2003, it has grown to 28% in 2012 (Figure 2-9). As different 3DP processes mature over time and move up in the MRL scale, direct part production should also increase.





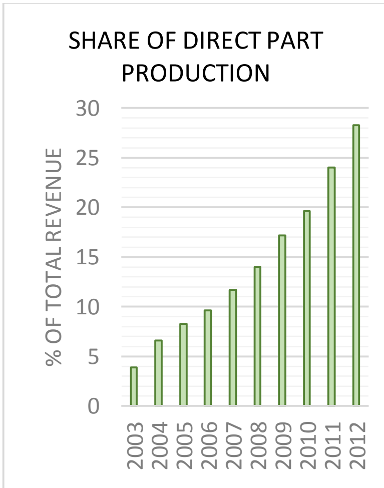


Figure 2-7 (Left) Personal 3D printers sold (Wohlers, 2012b; Denison, 2013)
Figure 2-8 (Middle) Professional grade 3D printers sold (Wohlers, 2013a; Wohlers, 2012c)
Figure 2-9 (Right) Share of direct part production of total 3DP revenue (RedEye, 2014)

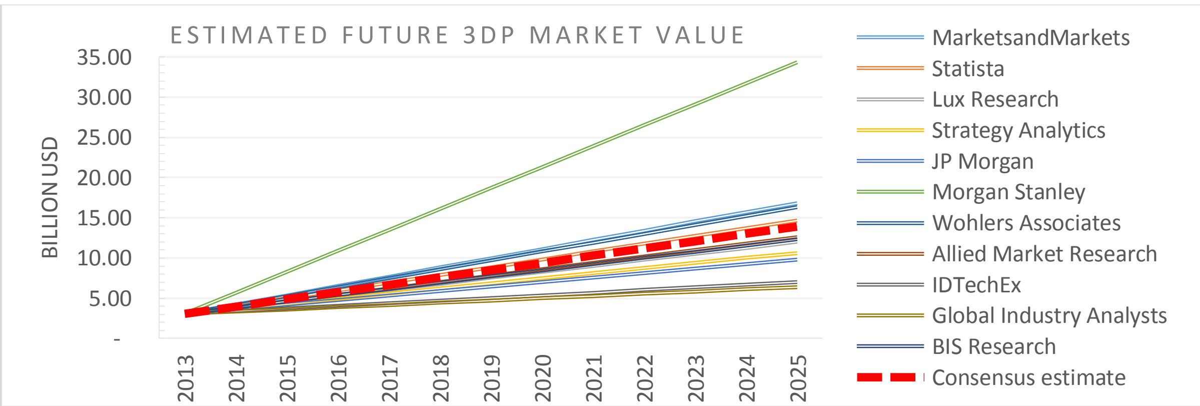


Figure 2-10 Future 3DP market value, consensus estimates (estimates until 2020 are extrapolated to 2025) (PRNewswire, 2014; Statista, 2014; Peach, 2014; Krassenstein, 2014; Briggs, Cotteleer, Brown, & Brown, 2014; Woodcock, 2014; Newman, 2014; Siemens, 2014; ASDReports, 2014)

The entire 3DP industry has experienced an impressive growth of 27% on average for the past 26 years. The global market for 3DP products and services grew to $3,07 billion in 2013 (Wohlers Associates, 2014). (Figure 2-6). It is believed the sector will continue with its growth the next decade. Figure 2-10 shows the estimated future 3DP market value by various analysts. The consensus expects the market will be worth $13,9 billion by 2025.

2.3.2 Technological trends in the 3D printing sector

Several technological improvements for 3DP technology are expected, following the 2009 industry roadmap (Bourell, Leu, & Rosen, 2009) for the next decade. These will make the technology more competitive with conventional manufacturing approaches.

Process improvements

Processes will continue to improve, with some advancing quicker than others. Stronger builds, smoother finishes, and multiple material depositions are made possible. Experts believe that hybrid technologies will appear that take advantage of both additive and subtractive processes (Shipp, et al., 2012). Another appealing development is the insertion of prefabricated components (e.g. circuitry) using additive processes.

Speed

Machine manufacturers will focus on increasing build speed through increased deposition rates in the near future (Shipp, et al., 2012), since current processes are still rather slow. The average production speed is expected to increase to at least 80 cm^3/h in 2017, 120 cm^3/h in 2020, and above 150 cm^3/h by 2023 (Figure 2-11). Since there is a trade-off between the built size and speed (Shipp, et al., 2012), larger sizes become more feasible when speed increases, and the build chamber volumes are expected to grow alongside the speed. The average build chamber volume will be increased to at least 1 m^3 in 2016, to 2 m^3 by 2020, and above 8 m^3 by 2023.

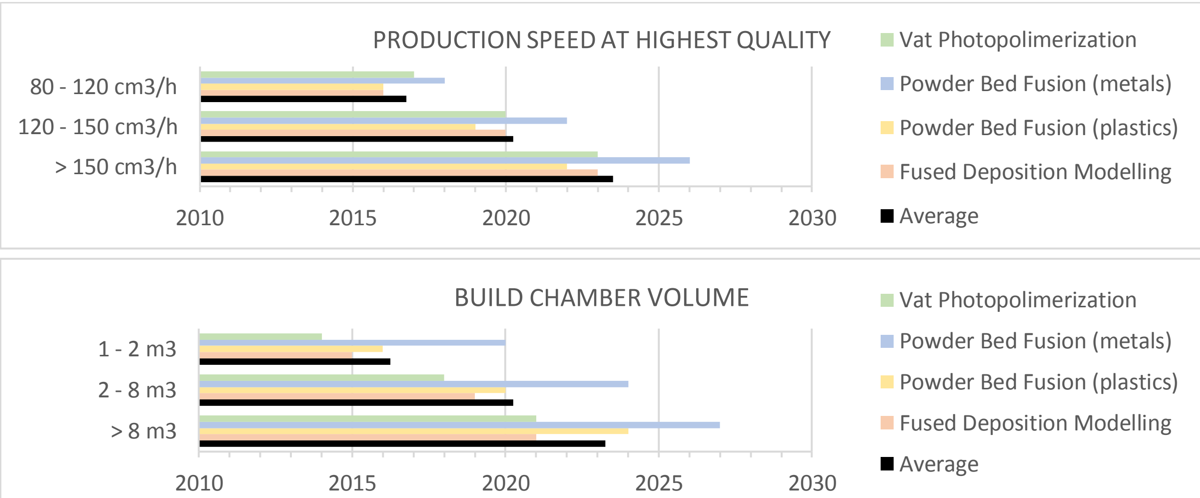


Figure 2-11 Expected production speed (top) and build chamber volume (bottom) in the near future, adapted from Gausemeier, Echterhoff and Wall (2013)

Quality control

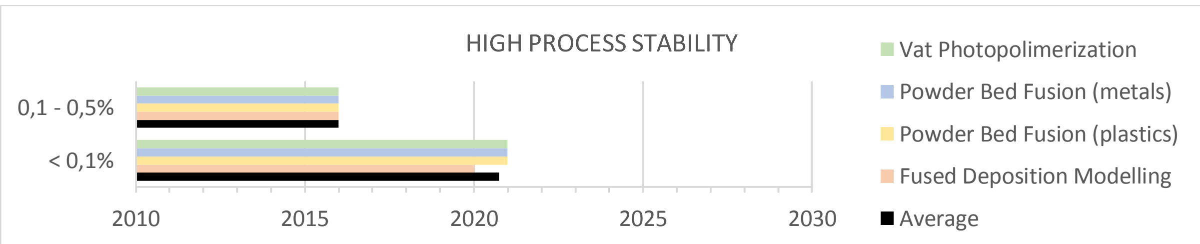


Figure 2-12 Expected process stability in the near future, adapted from Gausemeier, Echterhoff and Wall (2013)

In the coming years, processes will likely become more stable with better quality control systems. These systems will deal with material issues, such as thermal distortion between build layers and gas bubble inclusions, thus increasing the process stability (i.e. lower deviation of reproducibility), which is an important requirement for the penetration of 3DP in the future (Gausemeier, Echterhoff, & Wall, 2013). Most 3DP techniques will reach a process stability of 0,1-0,5% in 2016 and below 0,1% in 2021 (Figure 2-12).

Materials

Furthermore, there will be improvements in single materials for additive processes, as well as new combinations of materials. At the same time, competition in the 3DP materials market should reduce the prices. Metal 3DP will grow faster than plastic 3DP (Roland Berger Strategy Consultants, 2013), and metallic based 3DP processes are expected to reach almost half of the market share by 2015 and witness a steady growth until 2020. Multifunctional 3DP will start to make an entrance by 2015 and grow to about 10% by 2020 (AM Platform, 2014).

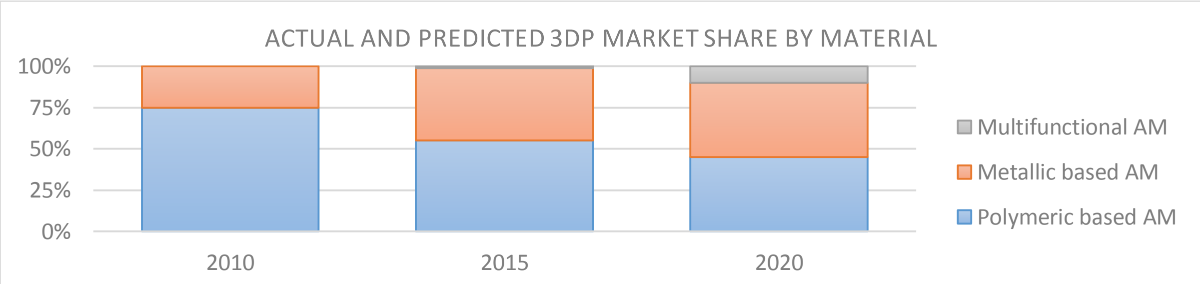


Figure 2-13 Actual and predicted 3DP market share by material, adapted from 3DP Platform (2014)

2.4 Chapter summary

The origin of 3DP technology can be found in the 40s alongside the invention of computers. But it is only until the last decade, advances of the technology has generated significant interest and activity in the industry. The wide variety of 3DP processes has been officially categorized recently as a step towards standardisation. The largest three contributing industries of the industry are consumer products/electronics, automotive, and the medical industry. In each industry, the common success factors are increased surface quality, new materials and increased reproducibility. 3DP processes are not fully matured yet. Only basic plastic processes are at the most advanced level ready for production implementation. High quality plastic and metal processes are halfway the MRL scale around the pre-production phase, while other material processes are still undergoing experiments. 3DP technology still needs continuous development and investment before a wide scale adoption is possible. Current trends show the industry is growing at a fast pace with an average annual growth of 27%. The lower 3D printer prices have sparked demand also from consumers. Particularly direct part production is gaining more relevance. Several technological improvements can be expected in terms process improvements, speed, quality control and materials the coming decade.

Illustration 7

Wall of 3D printed figures (The Science Museum, 2013)

Illustration 6

Lightweighted Airbus part (SolidSmack, 2012)

Chapter 3

The impact of 3D printing on manufacturing and supply chains

"Bits are thrilling, but when it comes to the overall economy, it's all about atoms."

Chris Anderson (2012), author and entrepreneur

In his book, Anderson (2012) argues that manufacturing is essential for a country's economy, and that even the service sector (such as the information industry, or "bits") is subject to and depend upon it. However, the same could be argued for the opposite, that manufacturing also depend on services in order to be useful. Today's products are rarely made and delivered by one party. Often it is the collaborative work of different specialists all adding value in a complex supply chain. Such as the logistics industry that provides a specialized service in facilitating the flow of goods between those different parties. Thus manufacturing requires a corresponding supply chain in order to be effective. In an ongoing globalizing world, in which firms are facing a more competitive global market, future manufacturing needs to be highly flexible, adaptable, and fast with respect to organization of production and supply chain management. With the rise of 3DP technology, how does it affect manufacturing and supply chains? The goal of this chapter is to assess how 3DP relates to current manufacturing and supply chain theories, and subsequently develop a score model to quantify the current impact of 3DP on manufacturing and supply chains. In Section 3.1, current manufacturing and supply chain theories are explored and assesses how 3DP relates. Section 3.2 examines the factors that determine the applicability of 3DP for manufacturing firms and uses these to create a score model that can be used to estimate the market penetration for various products. Section 3.3 examines the impact of 3DP market penetration on supply chains.

3.1 3DP in relation to manufacturing and supply chain theories

According to Porter (1985), businesses can achieve two basic types of competitive advantage: cost advantage or differentiation. Based on this theory he compiled the three generic business strategies, namely cost leadership, differentiation, and focus. It can be disputed whether “focus” is a generic strategy as it refers to the narrower scope of the business activity, but is also based on either cost leadership or differentiation. Others have pointed out firms are successfully employing a combination of both strategies, the so called “hybrid strategy” (Hambrick, 1983; Hill, 1988; Miller, 1992). For businesses to succeed, the competitive advantage strategy needs to align with the product characteristics, manufacturing and supply chain strategies. This alignment is shown in Table 3-1.

Table 3-1 An overview of corresponding business strategies, products characteristics, supply chain and manufacturing strategies (Mason-Jones, Naylor, & Towill, 2000; Gupta, Gollakota, & Srinivasan, 2007; Fisher, 1997; Huang, 2013; Hofmann, Beck, & Füger, 2013; Van Assen, Hans, & Van De Velde, 2000; Hayes & Wheelwright, 1979)

Competitive strategy	Cost leadership	Hybrid strategy	Differentiation
Supply chain goal	Efficient	Efficient/responsive	Responsive
Supply chain strategy	Lean	Leagile	Agile
Product type	Functional (commodity)	Hybrid	Innovative (fashion)
Product life cycle	Long (>2 years)	Long (>2 years)	Short (3-12 months)
Delivery lead time	Dispensable	Small	Large
Product volume	High	Medium to high	Low
Product variety	Low	Medium to high	High
Demand uncertainty	Low	Medium	High
Market driver	Forecast driven	Forecast driven until decoupling point, customer order driven faster decoupling point	Customer order driven
Internationalization	Global	Transnational	Multi-domestic
Centralization	Centralized production and shipments to markets	Combination of centralized, decentralized into a global network	Decentralized production situated in the respective host markets
Manufacturing process	Line process	Batch process	Job process
Manufacturing strategy	Make-to-stock	Assemble-to-order	Make-to-order
Market qualifying criteria	Time, flexibility, quality	Time, quality	Cost, time, quality
Market winning criteria	Cost	Cost/flexibility	Flexibility

According to Gupta, Gollakota, and Srinivasan (2007), cost leadership is associated with an “efficient” supply chain, and differentiation strategy with a “responsive” supply chain. Fisher (1997) proposed a model (empirically tested (Olhager, 2012)) for aligning the supply chains with the product type (Appendix C, Figure C-1). He concludes that “functional products” require an efficient supply chain and “innovative products” require a responsive supply chain. Also he determined the distinguishing characteristics of the two products. This has been further developed by Mason-Jones, Naylor, & Towill (2000) (Appendix C, Table C-1). The authors, and also Hofmann, Beck, and Füger (2013), determined that the efficient supply chain corresponds with the “lean paradigm”, and the responsive supply chain with the “agile paradigm”. A combination of a lean and agile supply chain has been named “leagile” (Huang, 2013; Hofmann, Beck, & Füger, 2013).

Others have described the alignment of the right structure with the supply chain paradigms. A decentralized structure is critical for achieving agility, as it allows its different segments to react to changing environment faster (Van Assen, Hans, & Van De Velde, 2000; Hofmann, Beck, & Füger, 2013).

A lean production system on the other hand performs better in a stable environment, thus a decentralized structure is not required (Krishnamurthy & Yauch, 2007). Furthermore, the alignment of product characteristics and supply chain with the manufacturing process and strategy has been described by Hayes and Wheelwright (1979) and Hofmann, Beck, and Füger (2013). A lean supply chain corresponds with a make-to-stock (MTS) manufacturing strategy, an agile supply chain with make-to-order strategy, and leagile with an assemble-to-order (ATO) strategy. Finally, supply chains have corresponding set of competitive priorities (Hofmann, Beck, & Füger, 2013). For a lean strategy, cost is the most important capability (market winner), while for the agile strategy this is flexibility. These will be explained further in the next section.

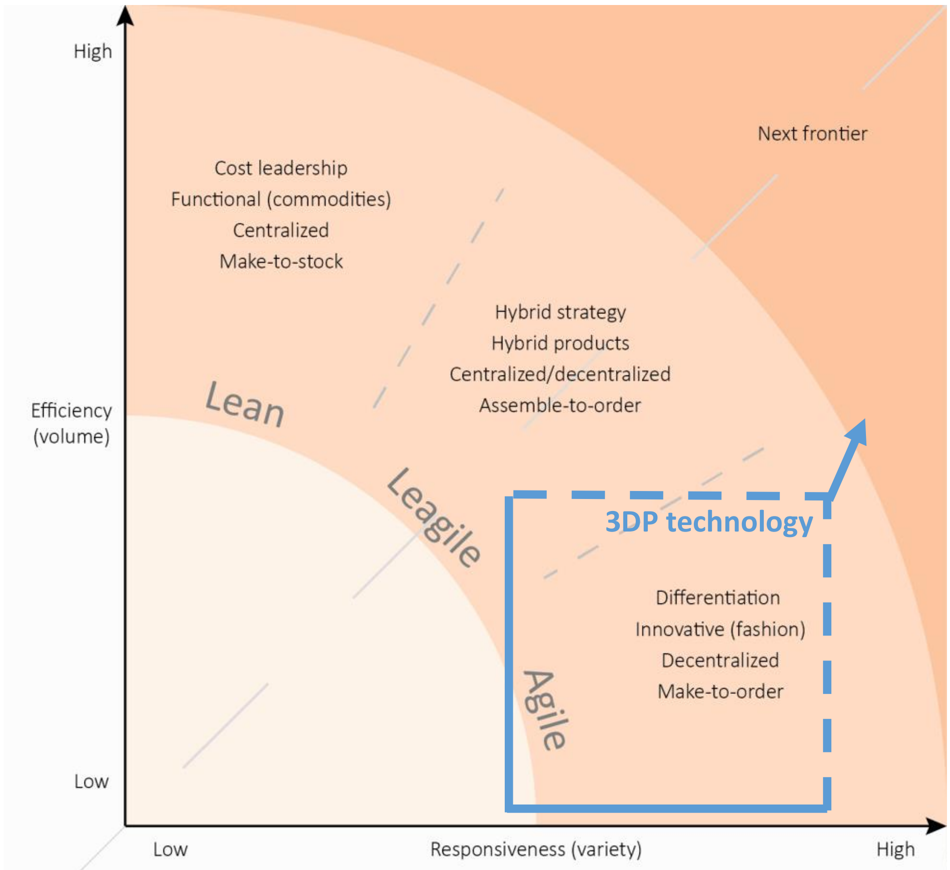


Figure 3-1 Consolidated matrix, showing the trade-offs in competitive strategies, products characteristics, supply chain and manufacturing strategy, based on Table 3-1.

Based on Table 3-1, a consolidated framework that illustrates the trade-offs can be shown (Figure 3-1). Typically there is a trade-off between efficiency and responsiveness, or volume and variety. Using this framework, the relative position of 3DP technology in relation to different industries can be depicted. 3DP technology currently belongs to the righter down corner. It is typically suited for products with high differentiation and low volume production requirements. As the technology progresses, gaining production speed and efficiency, its place in the graph should expand, making it more suitable for products with other market conditions and characteristics. The further away a certain product is from the "3DP border", the less applicable the technology is. This will help explain the success of 3DP in different industries. For an extended explanation of the lean, agile and leagile paradigms, refer to Appendix D.

3.2 The impact of 3DP on manufacturing

Whether 3DP as a production tool brings benefits to manufacturers depends various factors. In this subchapter, these factors (Section 3.2.1) will be determined and contained in a score model that can be used as an assessment/quantification tool (Section 3.2.2) to estimate the 3DP market penetration in the future for different products. Using market analyses, the model will be tested for validity (Section 3.2.3).

3.2.1 Manufacturing competitiveness through 3D printing

Businesses compete in the marketplace by virtue of one or more of the following competitive capabilities: quality, time, cost and flexibility (Figure 3-2) (Hayes & Wheelwright, 1984). The competitive capabilities are the critical operational dimensions a supply chain must possess. Other capabilities have been proposed over the years, such as 'innovation', 'service' or 'manufacturing technology', but the general consensus in literature defines the original four competitive capabilities as the generic components (Boyer & Lewis, 2002; Ward, McCreey, Ritzman, & Sharma, 1998; Amoako-Gyampah & Acquaah, 2008). As suggested previously, a lean supply chain will focus on Cost, while an agile supply chain on Flexibility. 3DP impacts all competitive capabilities. It can be assumed businesses are more likely to deploy 3DP, if it positively impacts their competitive capabilities, as it will increase their competitiveness. Each competitive capability has different dimensions. How 3DP influences each of these dimensions is discussed below, and in detail in Appendix E.

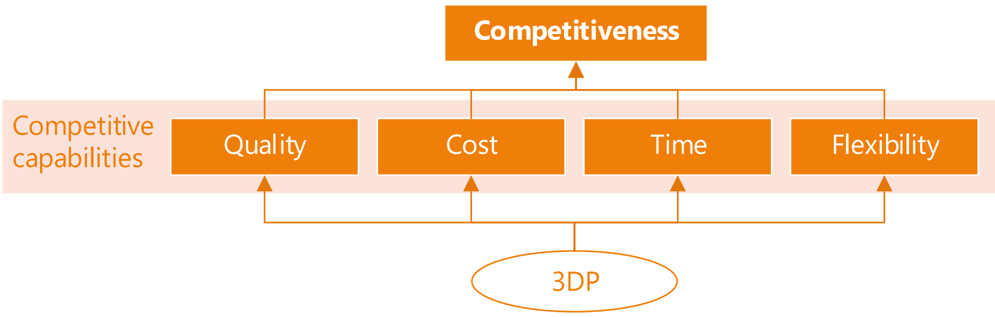


Figure 3-2 3DP influences the competitive capabilities of a firm

Dimensions of Quality

The (objective) quality of a product is determined by the performance of the following dimensions: Performance, features, reliability, conformance, durability, serviceability, and aesthetics. 3DP can improve some of them, but also diminish others.

- Performance refers to a product's primary operating characteristics (Garvin, 1987). Generally 3DP can be used to increase the product performance by "lightweighting" the structure through an internal honeycomb structure, if **light weight** is a requirement.
- Features are all the "whistles and bells" the product offers that supplement its basic functioning (Garvin, 1987). 3DP can generally be used to increase the ergonomics (or fit) of a product through easy personal customization, if **ergonomics** is a requirement, assuming it is considered a feature.
- Reliability is the likelihood of a product defect or breakdown within a time period (Garvin, 1987). 3DP will generally reduce the reliability of a product due to process instability. Reliability is acceptable using expensive industrial grade equipment. Thus 3DP is more suitable for products without a **safety** requirement.

- Conformance is the degree to which a product conforms to specifications or is produced correctly (Garvin, 1987). 3DP will generally reduce the conformance of a product due to limited processes robustness. Thus it is more suitable for products with a low **precision** requirement.
- Durability can be defined as the amount of usage one gets from a product before it breaks down and repair is not favourable (Garvin, 1987). 3DP will generally reduce the durability of a product due to process instability, thus it is more suitable for short **life cycle** products.
- Serviceability concerns the speed, courtesy, competence, and ease of repair (Garvin, 1987). 3DP can be used to increase the serviceability through on-demand spare part production. 3DP will benefits products that require **service and maintenance**.
- Aesthetics concerns how a product looks, feels, sounds, tastes, or smells and it is dependent on an individual's personal preference (Garvin, 1987). 3DP will benefit products with an **aesthetic** requirement as it offers higher design freedom.

Dimensions of Cost

The number of cost dimensions are too broad to all be considered, thus the most crucial cost, namely production cost, will be considered. Whether 3DP can be deployed to increase the cost performance (i.e. decrease production cost) depends on the following factors: Production volume, part size, (geometric) complexity, and material use.

- **Production volume** is the total units of a product variant produced per year. Compared to conventional manufacturing, 3DP generally has lower fixed cost (e.g. equipment cost) and higher variable cost (e.g. material cost), which makes 3DP more cost effective at lower production volumes.
- **Part size** greatly affects the 3DP production cost due to its low build speed. Larger parts take significantly longer to build than smaller parts, i.e. higher productivity can be achieved with smaller parts. Thus a smaller part size is more suitable for 3DP.
- **Complexity** slightly affects 3DP cost, but greatly affects conventional manufacturing cost. Geometrically complex products require more tooling, but not with 3DP as "complexity is for free". Thus more complex products are more suitable for 3DP.
- **Material** of the product affects the cost, as they determine the Manufacturing Readiness Level (Section 2.2.1) in 3DP. Higher MRL for a 3DP process linked to material means it is more ready towards full production, and thus is cheaper to utilize. It will be assumed products made of plastics are the most suitable for 3DP, then metals, and then other materials.

Dimensions of Time

Time concerns the speediness of delivery and development. It can be divided into the following dimensions: Delivery speed, and development speed (Laugen & Boer, 2011; Krajewski, Ritzman, & Malhotra, 2010).

- Delivery speed concerns the reduction in lead time from the receipt of a customer order to the product delivery (Krajewski, Ritzman, & Malhotra, 2010). It is a more important matter for customized products than for standard products, as the former cannot be stocked. 3DP speeds up customization through reconfiguration of the production process. It will be assumed 3DP will increase the delivery speed of products that require **customization**.

- The development speed is the rate of introducing a new products (Krajewski, Ritzman, & Malhotra, 2010). 3DP can be used to shorten the development phase through rapid prototyping. It will mainly benefit products in **innovative** sectors.

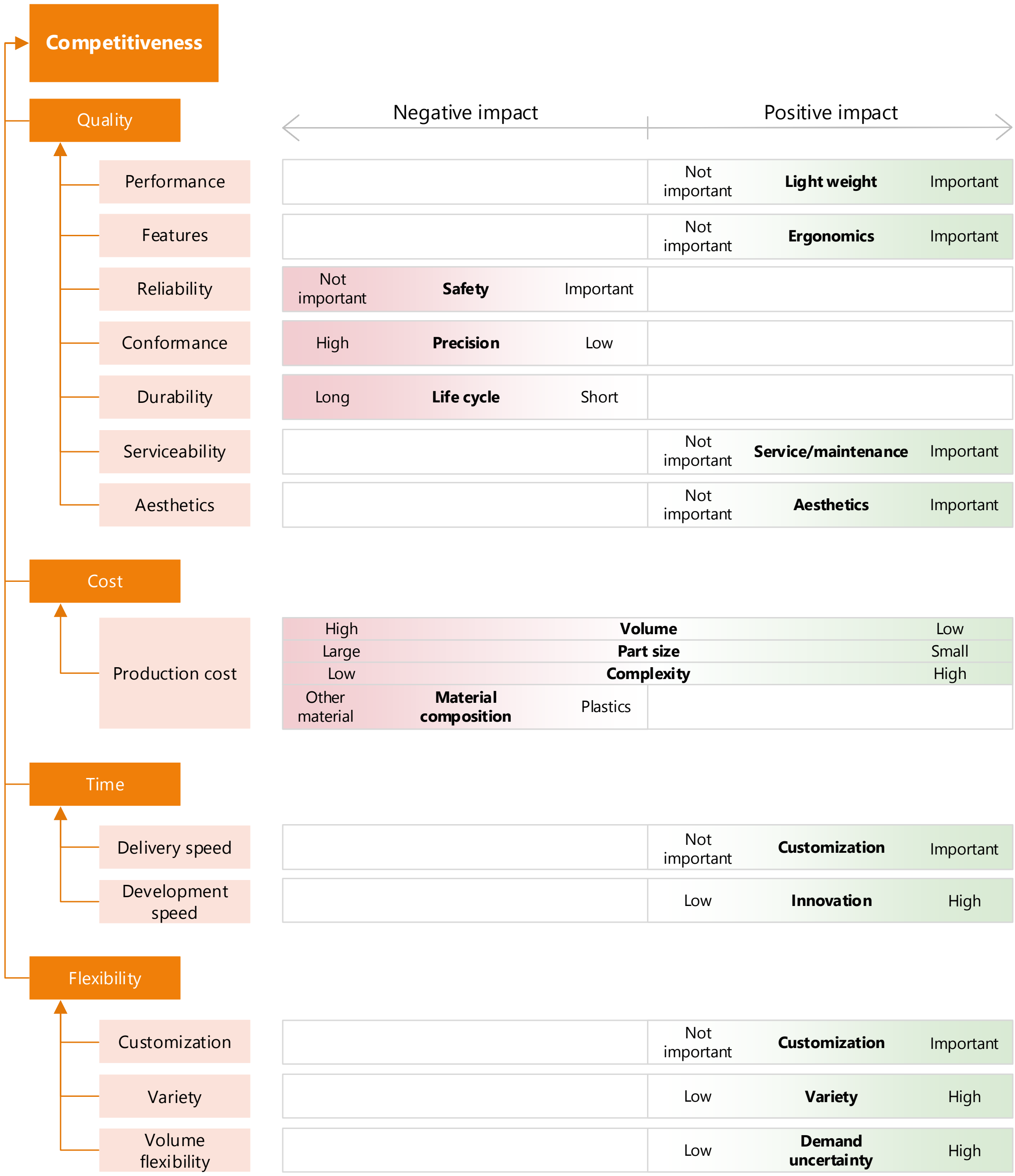


Figure 3-3 The impact of 3DP deployment on competitive capabilities of firms, depending on product and market characteristics

Dimensions of Flexibility

Companies require flexibility in their operations to deal with uncertainties. Flexibility can be divided into the following dimensions: Customization, variety, and volume (Krajewski, Ritzman, & Malhotra, 2010).

- Through customization, a firm can satisfy the unique needs of each customer by adapting product designs (Krajewski, Ritzman, & Malhotra, 2010). Due to the toolless nature of 3DP, it is highly suitable for customization and low volume production. Products that require **customization** will benefit from 3DP.
- Variety concerns the handling of a wide assortment of products (Krajewski, Ritzman, & Malhotra, 2010). Manufacturers create variety with limited complexity in the supply chain through postponement. 3DP should be able to aid manufacturers in the customization stage. Thus it can be assumed 3DP can beneficial for products that require **variety**.
- Flexibility in volume is the ability to adjust processes to handle demand fluctuations (Krajewski, Ritzman, & Malhotra, 2010). Products with a predictable demand are more likely to adopt a manufacturing and supply chain setup that maximizes cost efficiency, instead of flexibility (Hofmann, Beck, & Füger, 2013). Thus products with **uncertain demand** are more suitable for 3DP.

In summary

In this section, it is explained how 3DP influences the dimensions of the competitive capabilities. Depending on the product and market characteristics, 3DP deployment will have a positive or negative impact on the competitiveness of a firm. This is summarized in Figure 3-3. This figure will be used as the framework for the score model to estimate the future 3DP market penetration.

3.2.2 New framework to estimate the market penetration of 3D printing

Following the framework from the previous section, illustrated in Figure 3-3, the next score model (Table 3-2) is proposed. The score model proposes a systematic and qualitative tool that evaluates the potential increase in competitiveness that can be achieved through 3DP deployment.

Table 3-2 3D Competitiveness Score Model to determine the overall improvement of competitive capabilities through 3DP deployment

	Weight	Negative impact	← →	Positive impact
		-1	0	1
Quality	1			
Performance			Unimportance of light weight	Importance of light weight
Features			Unimportance of ergonomics	Importance of ergonomics
Reliability		Importance of safety	Unimportance of safety	
Conformance		High precision	Low precision	
Durability		Long life cycle	Short life cycle	
Serviceability			Unimportance of service/maintenance	Importance of service/maintenance
Aesthetics			Unimportance of aesthetics	Importance of aesthetics
Cost	1			
Production cost		High volume		Low volume
		Big part size		Small part size
		Low complexity		High complexity
		Other material	Plastics and metals	
Time	1			
Delivery speed			Unimportance of customization	Importance of customization
Development speed			Low innovation	High innovation
Flexibility	1			
Customization			Unimportance of customization	Importance of customization
Variety			Low variety	High variety
Volume flexibility			Low demand uncertainty	High demand uncertainty

The assumption is the more competitive capabilities that can be improved, the more competitiveness is achieved, the more likely 3DP will be deployed for a particular market, thus the higher the 3DP market penetration. Depending on the product and market characteristics, positive or negative impact can be made on the competitive capabilities of that firm. We will name it as the **3D Competitiveness Score Model (3DCSM)**. The determination of the relative and fuzzy values (e.g. low or high volume) can be found in Appendix F.

Each dimension is divided into three levels, namely potential for **negative impact**, **no effect**, or **positive impact**. Dimensions that can be enhanced through 3DP, either score a 0 (no effect), or a 1 (positive impact). Dimensions that can be diminished by 3DP, either score a 0 (no effect), or a -1 (negative impact). The scores will be averaged per competitive capability and normalized to 1. The total 3DCSM score will normalized against the maximum score. Equal weights per competitive capability is assumed for the sake of simplicity (see Appendix G). A calculation example for a hypothetical product is shown in Table 3-3.

Table 3-3 Example of a hypothetical product with no positive impact on the Time and Flexibility capability when using 3DP

Capability	Impacted dimension	Product characteristic	Score
Quality	Performance	Light weight requirement	+1
	Features	Ergonomics requirement	+1
	Reliability	Safety unimportant	0
	Conformance	Low precision	0
	Durability	Short life cycle	0
	Serviceability	Maintenance requirement	+1
	Aesthetics	Aesthetic requirement	+1
		Subtotal Quality score	**5 → 100%**
Cost	Production cost	Low volume production	+1
	Production cost	Small part size	+1
	Production cost	Highly complex	+1
	Production cost	Primarily plastic	0
		Subtotal Cost score	**3 → 100%**
Time	Delivery speed	Requires no customization	0
	Development speed	Not innovative sector	0
		Subtotal Time score	**0 → 0%**
Flexibility	Customization	Requires customization	0
	Variety	High variety	0
	Volume flexibility	High demand uncertainty	0
		Subtotal Flexibility score	**0 → 0%**
Total 3DCSM score			**50%**

3.2.3 Testing the 3D Competitiveness Score Model through market analyses

In order to validate that the 3D Competitiveness Score Model (3DCSM) is able to produce numbers that can predict the level of market penetration in a particular industry, it will be tested with several products from industries that are known for deploying 3DP. We will test three groups based on 3DP market penetration: medium-high 3DP adoption, low-medium 3DP adoption, and none-existent-low 3DP adoption (as control group).

- **Medium-high 3DP market penetration:** 3DP deployment for the direct production of dental crowns and hearing aids seems to be becoming rather common and the 3D printed variants are replacing conventionally made products, so the 3DP market penetration has been significant. Thus it is expected they will score positively using the 3DCSM.

- **Low-medium 3DP market penetration:** The deployment of 3DP to create parts on an average car today is present but still quite limited. Opportunity lies in the consolidation of parts to reduce cost, and lightweighting for a higher quality. 3DP has been used to build smartphone prototypes (Jacques, 2014), but most printed articles in this sector are external parts (e.g. accessories). Direct part production is more common for jewellery, as it is used by some jewellers and 3DP service providers to create unique pieces. For these three industries, most 3DP application is mainly used for prototyping, and to a small degree direct part production. So it is expected, 3DCSM should produce scores lower than the scores from the medical industry.
- **None-existent-low 3DP market penetration:** 3DP deployment in the tyres and rubber and glass container industry is mostly none-existent, to a highly limited amount for prototyping. The 3DCSM should produce the lowest number compared to the previous markets.

An extended market assessment can be found in Appendix H, and a detailed scoring using the 3DCSM can be found in Appendix I. The summarized results are shown in Table 3-4.

Table 3-4 3DCSM scores of crowns, car, and glass containers, in relation to the actual 3DP market penetration

3DP market penetration	Industry	Product group	3DP deployment	3DCSM scores
Medium-high	Medical	Dental crowns	Direct part production, prototyping	72,9%
Medium-high	Medical	Hearing aids	Direct part production, prototyping	87,5%
Low-medium	Automotive	Cars	Prototyping, limited direct part production	39,6%
Low-medium	Electronics	Smartphone	Prototyping, limited direct part production	56,3%
Low-medium	Consumer goods	Jewellery	Prototyping, direct part production	54,2%
None-existent-low	Tyres & rubber	Tyres	Prototyping	-8,3%
None-existent-low	Glass	Containers	Prototyping	4,2%

The 3DCSM scores from Table 3-4 T indicate that the 3DCSM seems able to produce scores that reflect the market potential (relative success) of 3DP in a particular industry, as higher scores indicate higher 3DP market penetration. However, given the high scores for most industries, the scores probably do not reflect the real 3DP market penetration. Medical industry products scored the highest (72,9%-87,5%), automotive, electronics, consumer goods industry products scored average (39,6%-54,2%), and tyres and rubber, and glass industry scored the lowest (-8,3%-4,2%). More products should be tested using the 3DCSM for a better validity. Due to the time constraint, the number of products to be tested has been limited to these seven products.

3.2.4 Section summary

In this subchapter, it has been established 3DP impacts the competitive capabilities of a firm positively or negatively depending on the firm's product and market characteristics. Based on this knowledge, a score model (the 3D Competitiveness Score Model) has been developed to predict the market penetration of 3DP in a certain industry. After comparing the score model scores with current market data, it seems to be able to produce scores that reflect the market potential of 3DP in a market as higher scores indicate higher market penetration. But the score does not reflect the true 3DP market penetration. Next, we will assess how 3DP deployment affects the supply chain in which a manufacturing firm operates.

3.3 The impact of 3D printing on supply chains

In the previous subchapter (Section 3.2), we have assessed how 3DP impacts manufacturing firms. In this subchapter, we will analyse the impact of 3DP market penetration on the supply chains of these firms. Depending on where in the supply chain 3DP is being deployed, it will have different impact on the logistics setup. First the generic supply chain (Section 3.3.1) will be introduced. Then, how the generic supply chain differs from the supply chains with 3DP deployment will be assessed (Section 3.3.2). Finally, the 3DCSM scores will be related to the decentralization level of supply chains (Section 3.3.3) based on case studies.

3.3.1 Generic supply chains

As products today get more advanced and complex, so will the supply chains. The making of a highly complex product, like a modern day car, involves the collaboration of many suppliers and distributors. To give an indication, a Volkswagen Golf 2007 model has parts sourced from over fifty different suppliers (Wingett, 2008); or Ford Motor Company purchased parts from 1.260 suppliers (Trudell, 2013) and has 11.790 dealerships worldwide in 2011 (Ford, 2012). A manufacturer, liked Volkswagen or Ford, which customizes and incorporates sourced products and sells them under its own brand, is called an **Original Equipment Manufacturer (OEM)**. Figure 3-4 shows a typical supply chain structure (Supply chain 0 (SC0)) in the automotive industry. The arrows represent the material flow.

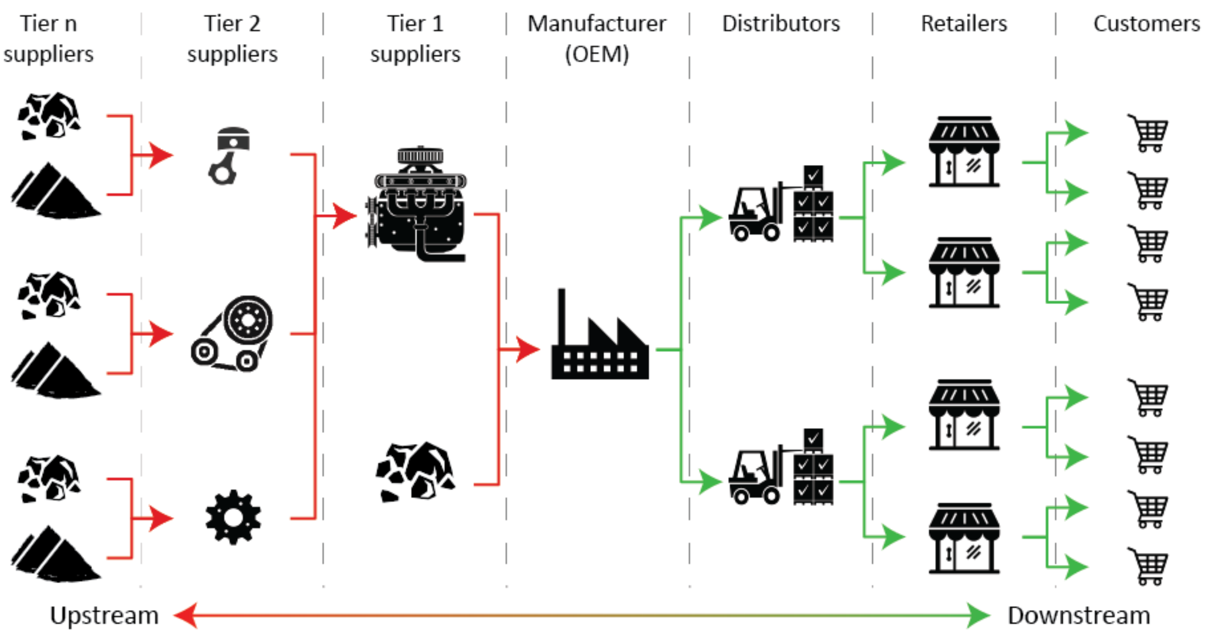


Figure 3-4 Supply chain 0, a typical supply chain structure in the automotive industry, adapted from GXS (2014).

Suppliers

Suppliers that directly supply the OEMs are called the tier 1 suppliers. These are the most important suppliers with whom OEMs develop close business relationships. They typically supply some of the largest sub-systems or **modules** (GXS, 2014; Swamidass, 2014), such as the car engine or the gearbox. Moving upstream, the tier 2 suppliers provide the tier 1 suppliers with **simpler components**, such as the distribution belt, cylinders, or gears. The more upstream tiered suppliers (tier n) provide its buyers with increasingly less complex components, such as **raw materials**. This pyramid shaped hierarchy is exemplar for today's supply chains (also called a tiered supply chain).

Distributors

The finished products are usually transported by third party logistics providers (3PL) to regional distribution centres and warehouses where they are temporarily stored and sorted. Moving further downstream, the products are then further distributed among local retailers where they can be purchased by the customers. The local retailers can be considered the 2nd tier of distributors.

3.3.2 Deployment of 3D printing in supply chains

In manufacturing, typically two types of structures can be distinguished, namely centralized or decentralized manufacturing. **Centralized manufacturing (CM)** focuses on production efficiency rather than responsiveness, and rely on bulk transport, such as container transport, to move their goods to regional distributors over the world. With **decentralized manufacturing (DM)** the production setup is more spread-out across the globe and is closer located to the consumer, which enhances the responsiveness to the market. It can be said that CM has the production site closer to the supply side, while DM has the production site closer to the demand side. For a more detailed explanation about CM, DM, and hybrid structures, refer to Appendix J.

3DP can be deployed in both types of structures. In fact, based on market analyses, generally five types of structures with 3DP deployment can be distinguished. A comparison can be drawn with the generic supply chain (Supply chain 0, Figure 3-4), to assess the impact of 3DP. The scope will be limited to the logistics configuration between the manufacturer and the end user, as the supplying side can be vastly complex and is less likely to deploy 3DP.

Supply chain 1

In supply chain 1 (SC1) (Figure 3-5), 3DP is deployed by the R&D. The supply chain can be considered conventional (similar to SC0), which operates through a centralized setup, with regional distribution, and local retailing. The supply chain is unaffected by the 3DP deployment, since only the design process is accelerated, but the actual manufacturing and delivery time is not reduced. A manufacturing company that adapts its supply chain from SC0 to SC1, will not change the existing logistics configuration. Goods will still flow from the supplier, to the manufacturer, to the distributor and retailer.

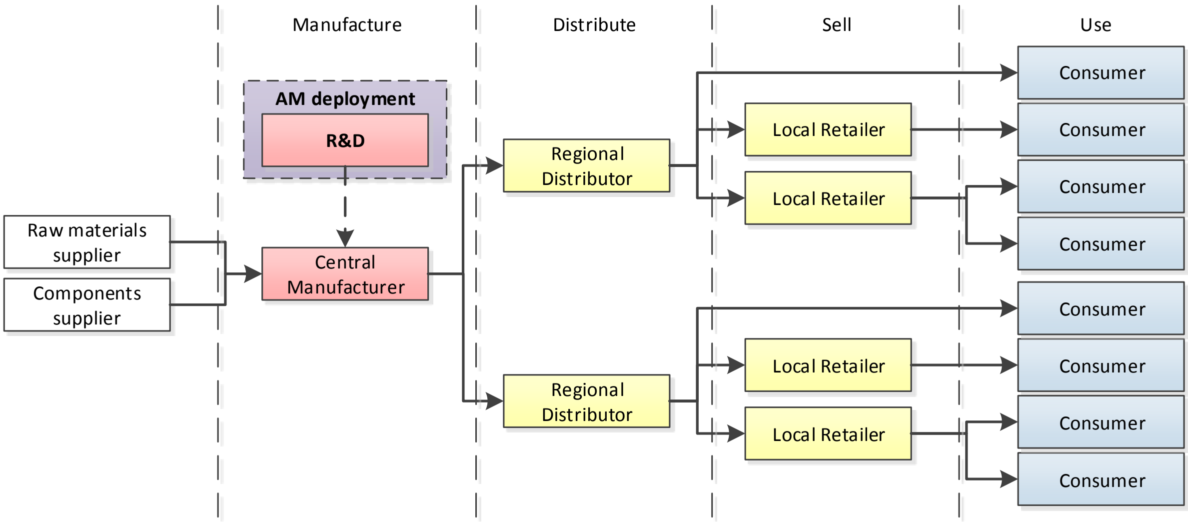


Figure 3-5 Supply chain 1 (SC1)

Supply chain 2

In supply chain 2 (SC2) (Figure 3-6), 3DP is deployed by the central manufacturer. There, 3DP can work complementary to conventional manufacturing processes. The manufacturing process is still centralized, and the supply chain relies on regional distributors and local retailers for distribution. The manufacturing process might be enhanced by the 3DP deployment, but it has not resulted in any change for the logistics configuration as all the transport links between all parties are still required.

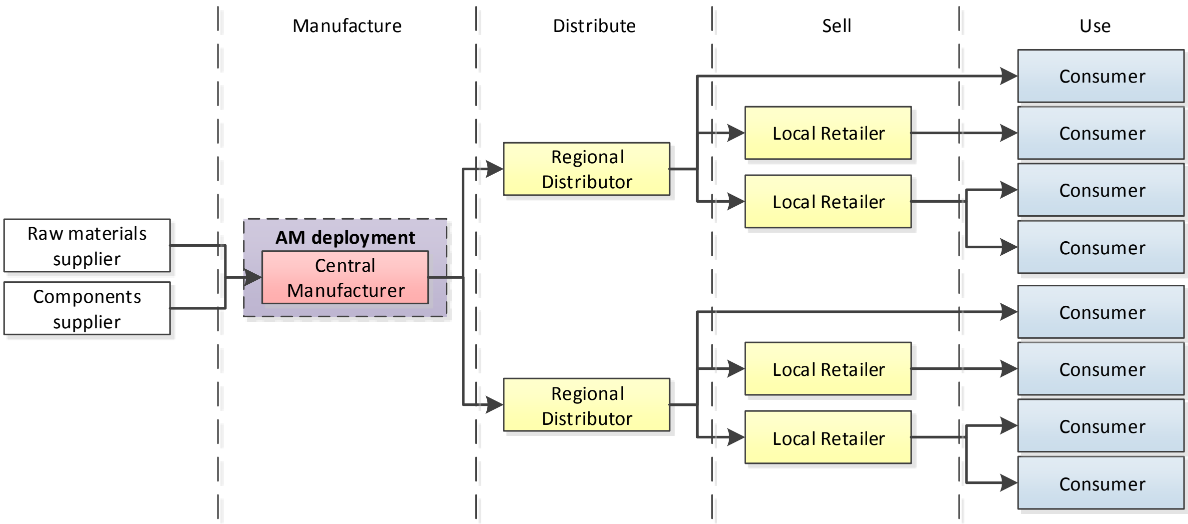


Figure 3-6 Supply chain 2 (SC2)

Supply chain 3

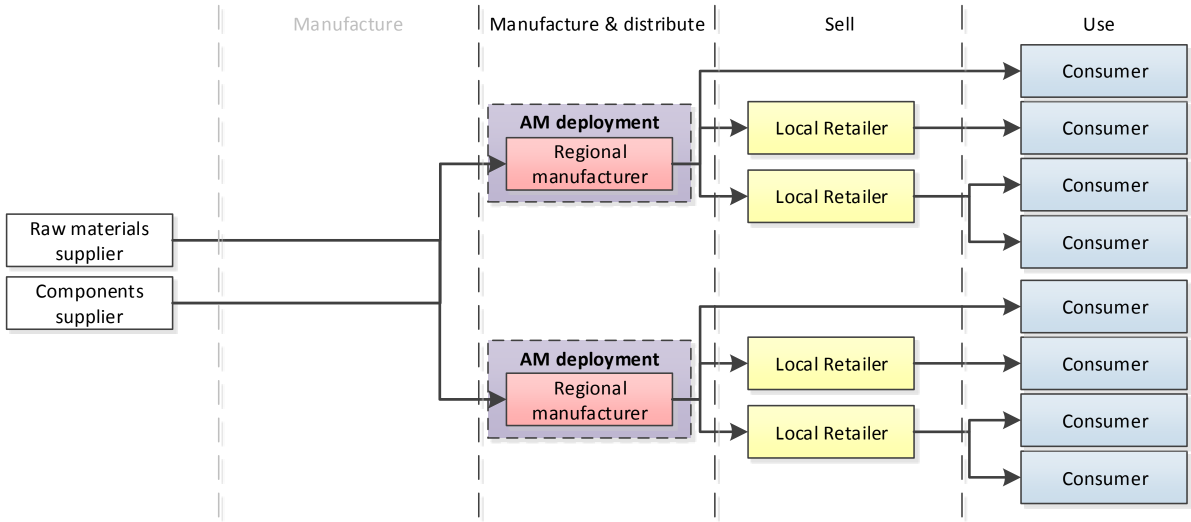


Figure 3-7 Supply chain 3 (SC3)

In supply chain 3 (SC3) (Figure 3-7), the manufacturing processes are situated at regional locations, thus this type of supply chain can be described as semi decentralized. Faster deliveries and responsiveness is achieved as the products are closer to the consumer. The manufacturer can have their own distribution centre near the production plant or can lease a regional distribution centre.

Supply chain 4

In supply chain 4 (SC4) (Figure 3-8), 3DP is deployed even closer to the consumers. Instead of regional manufacturing, the products are produced in local areas (city level). An even higher level of decentralized setup is achieved, which results in faster delivery and responsiveness compared to SC3. The benefits might come at the cost of efficiency as not all machines will be evenly utilized in case of a self-owned shop.

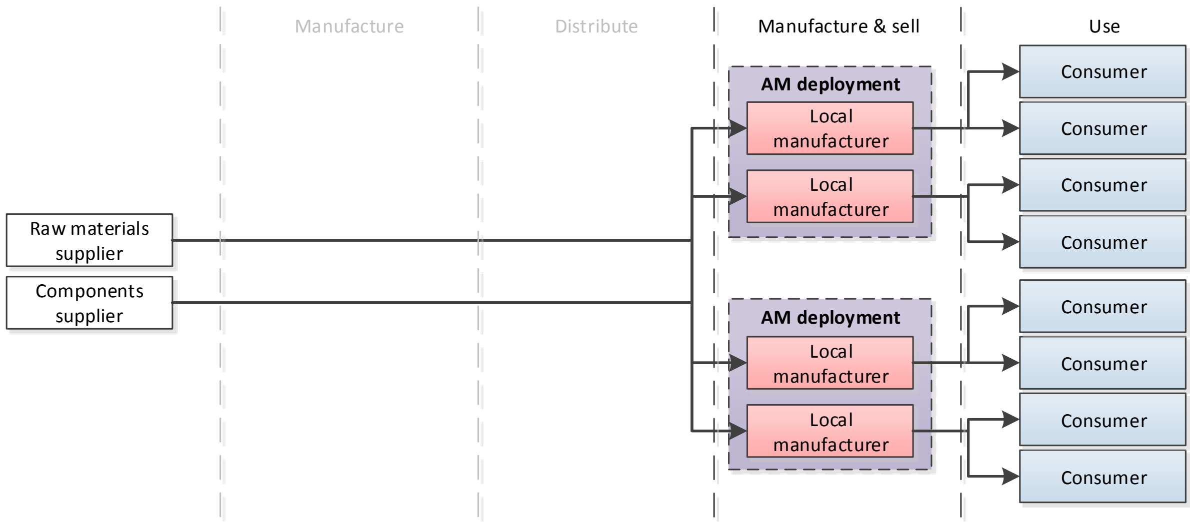


Figure 3-8 Supply chain 4 (SC4)

Supply chain 5

The highest level of decentralization is achieved with supply chain 5 (SC5) (Figure 3-9), which has 3DP deployment at the consumers' homes. The consumer can self-manufacture the products using a design provided by the manufacturer. Every middleman is eliminated, and thus the supply chain is the most different from the current typical supply chain (supply chain 0). Delivery time is reduced to zero and the only lead time is the actual printing time. However, it is also the most inefficient in terms of machine utilization compared to other supply chains.

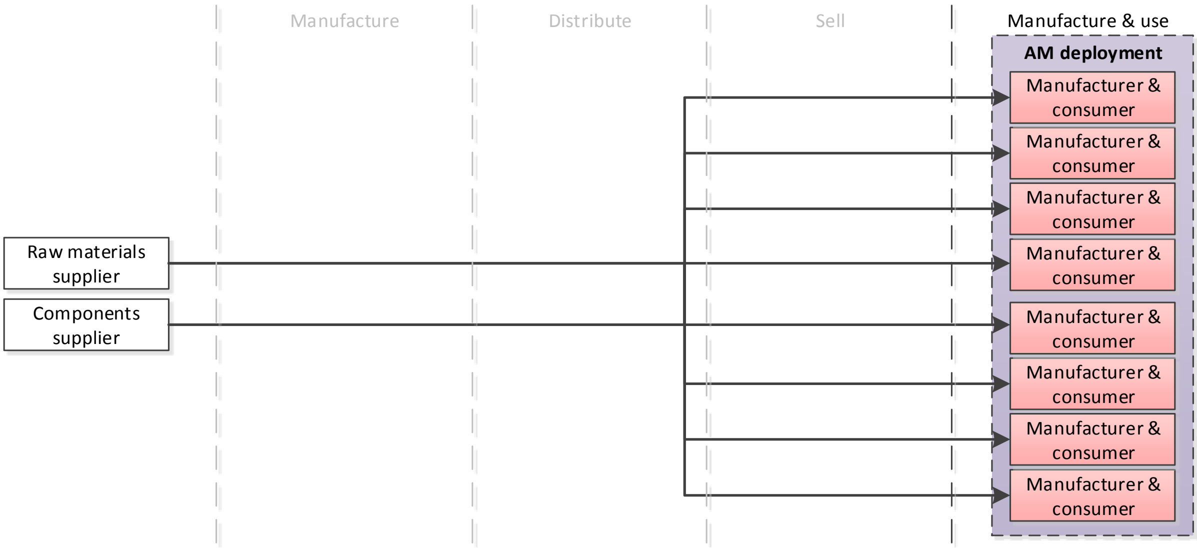


Figure 3-9 Supply chain 5 (SC5)

Supply chains of industries with 3DP deployment

Five types of supply chains with 3DP deployment have been distinguished. Their key characteristics can be summarized in Table 3-5.

Table 3-5 Key characteristics of 3DP deployed supply chains compared to the typical supply chain (SC0)

Supply chain	Description	Manufacturing setup	Transport distance supplier-manufacturer	Transport distance manufacturer-consumer	Exemplar industries
SC0	Generic	Centralized	Short	Long	- Glass - Tyres & rubber - Electronics
SC1	3DP prototyping	Centralized	Short	Long	- Automotive - Aerospace - Textile - Furniture
SC2	3DP for final production	Centralized	Short	Long	- Automotive - Aerospace - Medical - Jewellery
SC3	3DP for final production	Semi decentralized	Medium	Medium	- Medical - Miscellaneous consumer goods
SC4	3DP for final production	Decentralized	Long	Short	- Medical - Jewellery - Miscellaneous consumer goods
SC5	3DP for prototyping or final production	Fully decentralized	Long	None	- Miscellaneous consumer goods

SC0, SC1, and SC2 can be considered CM supply chains, while SC3, SC4 and SC5 can be considered DM supply chains. Higher decentralization levels result in shorter transport distance of materials between the manufacturer and the consumer, but a longer distance between the supplier and the manufacturer. In DM, raw materials and components are transported to multiple local places, instead of one central location. Thus a DM setup simplifies the transport on the manufacturer-consumer side (demand side), but complicates the supplier-manufacturer side (supply side) transport of the manufacturer.

Maritime transport is mainly meant for long distance transport. Thus it is likely DM and semi-DM do not require maritime transport between the manufacturer-consumer side, but only requires maritime transport for the supplier-manufacturer side. Following the notion that the total amount of material transported in a system must stay the same, regardless of changing the setup from CM to DM, the following assumption can be made:

If manufacturing shifts from CM to DM, material flow through maritime transport at the manufacturer-consumer side will be replaced by the same amount of material flow through maritime transport at the supplier-manufacturer side.

3.3.3 The relationship between the 3DCSM score and the decentralization level

3DP market penetration data does not show how the 3DP supply chains in these markets are organized. To get an indication of how current 3DP market penetration is coupled with the decentralization level of the supply chains, two markets will be assessed. However, such information is still highly limited. Only two markets have been found to report such information, namely the dental implants and hearing aid industry (Appendix K).

Based on the true market penetration and decentralization data, the relationship between the 3DCSM score and the decentralization level can be formulated. This step is necessary to convert 3DCSM scores eventually to the amount of change in transport volume. Table 3-6 shows an overview of the 3DCSM scores (Section 3.2.3) with the corresponding decentralization levels. For simplification, the total decentralization level includes DM and semi DM levels.

Table 3-6 3DCSM scores and manufacturing decentralization level of crowns, hearing aid, and other industries

Decentralization level	Non-existent-low 3DP market penetration	Low-medium 3DP market penetration	Medium-high 3DP market penetration	
Industries	Tyres, glass	Automotive, electronics, consumer goods	Crowns	Hearing aids
3DCSM score	**<0% (average)**	**48% (average)**	**72,9%**	**87,5%**
Total 3DP market penetration	No data, <0,1% (estimate)	No data, <10% (estimate)	25%	90%
Centralized 3DP (SC2)	No data	No data	7,5%	46%
Semi decentralized 3DP (SC3)	No data	No data	12,5%	44%
Decentralized 3DP (SC4)	No data	No data	5%	0%
Total decentralized 3DP	**0% (estimate)**	**<2% (estimate)**	**17,5%**	**44%**

Following the decentralization levels of the dental implants industry, a 3DCSM score of 72,9% for crowns (Table 3-4) currently corresponds with a total 3DP market penetration of 25%. Of this amount, 7,5% of 3DP is used at centralized level (SC2), 12,5% at semi-decentralized level (SC3), and 5% at decentralized level (SC4). So a total decentralization level of 17,5% is assumed.

The 3DCSM score of 87,5% for hearing aids corresponds with 90% market penetration, of which 3DP deployment happens for 46% at centralized level, and 44% at semi-decentralized level (SC3). So a total decentralization level of 44% is assumed. As for the industries with lower 3DP market penetration, the total decentralization level is assumed to be less than 2%.

The **total decentralization level** in relation to the 3DCSM scores are plotted in Figure 3-10. The regression line that follows (with a fit of $R^2=1$) will be assumed to reflect the relationship between the other 3DCSM scores and decentralization levels. Admittedly the used data to fit this graph is highly limited, it is however the best at hand.

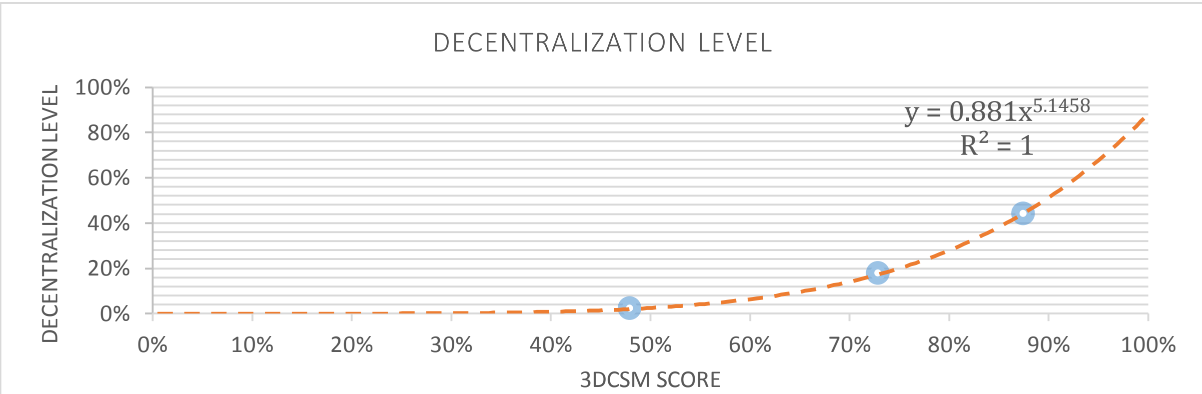


Figure 3-10 Estimated decentralization level in relation to the 3DCSM score

The formula that describes the relationship between SDCSM score and the decentralization level is the following power function:

$$y = \beta x^{\alpha}$$

where

y	Decentralization level
x	3DCSM score
α	Exponential constant, 5,1458, based on the decentralization level data
β	Second coefficient of x, 0,881, based on the decentralization level data

Based on the notion that products produced using DM and semi DM in do not require maritime container transport between the manufacturing site and the consumers' location(Section 3.3.2), it can assumed that the decentralization level equates to the percentage reduction in transport volume for finished products on the manufacturer-consumer side, and equates to the percentage increase in transport volume of raw materials (to produce these finished products) on the supplier-manufacturer side.

3.4 Chapter summary

In this chapter, the goal was to examine how 3DP technology impacts manufacturing and supply chains.

In Section 3.1, current theories have been introduced to better understand how 3DP as a new manufacturing tool fits current manufacturing and supply chain paradigms. Currently 3DP fits well with high differentiation and low volume production requirements. The further away from the "3DP bubble", the less suited 3DP is for a certain market. As the technology progresses, the bubble should extent to suit more markets.

Section 3.2 focuses on assessing and quantifying the impact of 3DP on manufacturing. It has been elaborated how 3DP impacts the competitive capabilities of manufacturing firms.

- Depending on the product and market characteristics of the firm, 3DP can impact the dimensions of the competitive capabilities Quality, Time, Cost and Flexibility differently.
- 3D Competitiveness Score Model has been compiled as a qualitative assessment tool to measure the potential market potential of 3DP in various industries.
- The score model is tested using various products from industries that were known for deploying 3DP.
- The 3D Competitiveness Score Model seems to be capable of producing numbers that reflect the 3DP market potential in a certain sector. Higher scores indicate higher competitiveness can be achieved, thus higher market penetration should follow.

In Section 3.3, supply chains with 3DP deployment has been compared with the generic supply chain to examine the impact. The analysis generated the following findings:

- 3DP has been deployed throughout the entire supply chain by different industries; some only for prototyping, others also for final production.
- 3DP has been deployed in centralized as well as decentralized manufacturing setups.
- Case studies of the dental implants and hearing aid industry suggest a high 3DP market penetration also leads to the decentralization (localization) of manufacturing.
- Market data from the case studies have been used to formulate the relationship between 3DCSM scores and the decentralization level.

Key assumptions

- If manufacturing shifts from centralized manufacturing to decentralized manufacturing, material flow through maritime transport at the manufacturer-consumer side will be replaced by the same amount of material flow (plus waste material during production) through maritime transport at the supplier-manufacturer side.
- The relationship between 3DCSM score (x) and the decentralization level (y) in a market can be formulated as:

$$y = 0{,}881x^{5{,}1458}$$

- The decentralization level equates to the percentage reduction in transport volume for finished products on the manufacturer-consumer side, and equates to the percentage increase in transport volume for raw materials (to produce these finished products) on the supplier-manufacturer side.

Chapter 4

Future impact of 3D printing

"The world potential market for copying machines is 5000 at most."

IBM, turning down the founders of Xerox, 1959

"There's no chance that the iPhone is going to get any significant market share. No chance."

Steve Ballmer, former CEO of Microsoft, 2007

"In five years, I don't think there will be a reason to have a tablet anymore…Tablets themselves are not a good business model."

Thorsten Heins, former CEO of Blackberry, 2013

Even industry leaders sometimes have a hard time predicting the future. While every assumption made in this report is carefully deliberated, many uncertainties still remains. Scenarios will be used to explore the range of possible futures. In the previous chapter, it has been established that decentralized manufacturing reduces the transport need at the manufacturer-consumer side, and increases the transport need on the supplier-manufacturer side. How will this allocation of transport flows impact the world container transport in the future? To forecast the future 3DP impact on the world container transport, a modelling approach is used as methodology. First, different levels of technological developments in the 3DP sector will be assumed to form the scenarios (Section 4.1). Second, the current maritime transport and its commodity flows will be assessed to explain the relationship between decentralization level and commodity flows (Section 4.2). Finally, the World Container Model (WCM) will be introduced and how its input data is compiled will be explained. The model will form the basis for assessing the future impact of 3DP on the world container transport (Section 4.3).

4.1 Future scenarios and matching 3D Competitiveness Score Models

3DP adoption in the future will mainly depend on technological improvements in the field that help overcome its barriers today. As 3DP technology advances, it will change the 3D Competitiveness Score Model and the scores it produces, as the determined impacts only reflect today's circumstances. Five scenarios will be presented. Three will have a low (Section 4.1.2), medium (Section 4.1.1) and high technological advancement rate (Section 4.1.3). The fourth scenario (Section 4.1.4) will be a medium scenario incorporated with the Global Innovation Index. A fifth extreme scenario (Section 4.1.5) is presented to test the upper bound of the 3DP impact.

4.1.1 Scenario M – Medium advancement rate in 3D printing technology

The medium 3DP future scenario (Sc. M) for 2035 will be based on the 3DP technology's innovation roadmap (Section 2.3.2), which already presents forecasts for the technology until 2025. The Sc. M will assume continued political and economic stability that currently exists. Other external factors are not considered, such as social, environmental, and technological factors, due to limited scope of this paper.

Production speed

An increased production speed means that higher production volumes or bigger part sizes can be achieved. The average production speed will have quadrupled by 2023 (Section 2.3.2), assuming an average production speed of about 40 cm^3/h today (Gausemeier, Echterhoff, & Wall, 2013). This means in 2023 >4.000 units per year and >4.000 cm^3 are the new definitions of respectively "high production volume" and "big part size". An extrapolation until 2035 gives 7.000 units/year and 7.000 cm^3. We will assume that at a production volume of 100.000 units/year 3DP has matched the production speed of conventional production methods. This means if 1.000 units/year represent a penalty of 1 in the 3DCSM today, then 7.000 units/year equates to a penalty of 0,93 in the 3DCSM relative to today's penalty. The same reasoning for "big part size" is assumed.

Process stability

A high process stability is considered to be an outstanding requirement for 3DP market penetration in the future (Gausemeier, Echterhoff, & Wall, 2013). It is unclear how much the current average process stability level is, presumably above 0,5% (Meyer, 2011). In comparison, injection moulded parts have a deviation of between 0,5-0,07% (Xu, Wu, Zhu, & Zhang, 2011). The process stability is a requirement that likely affects the reliability, durability, and conformance dimensions. Higher process stability reduces the amount of errors in production and thus increases the conformance level, which in turn should increase the reliability and durability. By 2021, 3DP processes will have reached process stability of <0,1% (Gausemeier, Echterhoff, & Wall, 2013), comparable to the process stability of injection moulding today. Thus in the 3DCSM for 2035, it is assumed this development will reduce the penalty for product characteristics "high precision", "safety importance" and "long life cycle". Instead of a penalty of 1, a reduced penalty of 0,25 is assumed.

3D printing material market

Most common commercial materials for 3D printing today are photopolymers, thermoplastics, metal powders and other powders (gypsum, ceramics, sand, glass, etc.). In 2013, of the total 2500 tons of materials produced, plastics accounted for 98%, metal accounted for 1,4%, and other powders 0,6% (Kneissl, 2013). The market for metal powders will experience the highest growth in production, currently at less than 30 tons/year. Also a reduction in material prices is predicted by various sources. The total 3D printing materials market is expected to worth $409 million in 2018 of which 51% is contributed by plastics (Taylor, 2013), and the rest mostly by metals (AM Platform, 2014). The total materials market is expected to be worth more than $600 million by 2025 (Kneissl, 2013). It will be assumed by 2035, metal processes will have reached the same production efficiency as plastic processes. Thus in the 3DCSM, instead of a penalty, metal processes will be changed to neutral same as plastic processes.

4.1.2 Scenario L – Low advancement rate in 3D printing technology

Scenario L (Sc. L) will be based on Sc. M, but with lower technology advancement rates.

Production speed

Instead of quadrupling twice the next two decades, by 2035 the production speed reaches the same speed as in 2023 from Sc. M. So in 2035 >4.000 units per year and >4.000 cm^3 are the new definitions of respectively "high production volume" and "big part size". Assuming that at a production volume of 100.000 units/year 3DP has matched the production speed of conventional production methods, and 1.000 units/year represent a penalty of 1 in the 3DCSM toay, then 4.000 units/year equates to a penalty of 0,97 in the 3DCSM. The same reasoning for "big part size" is assumed.

Process stability

Also the process stability has not increased in this scenario as much as in Sc. M. The process stability of 3DP still lacks behind of conventional manufacturing processes despite the technological developments by 2035. Instead of a penalty of 1, for products that have a safety requirement, high precision requirement, or have long life cycle, the penalty will be reduced to 0,50.

3D printing material market

By 2035, 3DP metals prices are still high. Plastics still dominate the 3DP materials market. Other powders (gypsum, ceramics, sand, glass, etc.) are still in development, but with no commercial breakthrough. Thus in the 3DCSM, no change for the materials is considered.

4.1.3 Scenario H – High advancement rate in 3D printing technology

Scenario H (Sc. H) will be based on Sc. M, but with higher technology advancement rates.

Production speed

In this scenario, the production speed increases exponentially, quadrupling twice in the next two decades until 2035. This means >16.000 units per year and >16.000 cm^3 are the new definitions of respectively "high production volume" and "big part size". Assuming that at a production volume of 100.000 units/year 3DP has matched the production speed of conventional production methods, then 16.000 units/year equates to a penalty of 0,84 in the 3DCSM. The same reasoning for "big part size" is assumed.

Process stability

Technological developments has led to a 3DP process stability that matches conventional manufacturing processes by 2035. Instead of a penalty of 1, for products that have a safety requirement, high precision requirement, or have long life cycle, no more penalty will be assigned to these product requirements.

3D printing material market

By 2035, not only 3DP plastics and metals have dropped significantly in prices, ceramics have also become a common 3DP material. Thus in the 3DCSM, no penalties will be assigned for products made of plastics, metals and ceramics.

4.1.4 Scenario Mi

Scenario Mi is based on Sc. M, but incorporates the Global Innovation Index (GII) (Cornell University, INSEAD, and WIPO, 2014). The GII is a conceptual framework that ranks countries based on their enabling environment to innovation and their innovation outputs. It uses 60 hard data, 19 indices and 5 survey metrics to compile a final score. Assuming countries with high GII scores are more likely to adopt new technologies, such as 3DP, it will be used as a parameter to adjust the decentralization rate per country. The highest and lowest GII scores (Appendix L) will be normalized to respectively increase and decrease the decentralization level by 25%. Countries not included in the GII study will be assigned a low GII score, which are usually countries with low GDPs.

4.1.5 Scenario X – Extreme advancement rate 3D printing technology

This scenario is to test the upper bound of the 3DP impact, and is thus highly unlikely to occur within the next 20 year timeframe. In this scenario all 3DP technological barriers are solved, except for materials. This means that if a product consists of a material that can be 3D printed, conventional manufacturing has no advantage over 3DP. Thus, products will score full points in the 3DCSM if the material is suitable.

3D printing material market

By 2035, like in scenario H, 3DP plastics, metals, and ceramics have dropped significantly in prices, and have become common materials. An additional material is added to this scenario, namely glass. Thus in the 3DCSM, no penalties will be assigned to the aforementioned products.

Table 4-1 Adapted variables in the 3D competitiveness score model per scenario

Competitive capabilities	Characte-ristics	Present	Sc. L	Sc. M	Sc. Mi	Sc. H	Sc. X
Quality							
Reliability	Importance/ unimportance of safety	-1/0	-0,5/0	-0,25/0	-0,25/0	0/0	-
Conformance	High/low precision	-1/0	-0,5/0	-0,25/0	-0,25/0	0/0	-
Durability	Long/short life cycle	-1/0	-0,5/0	-0,25/0	-0,25/0	0/0	-
Cost							
Production cost	High/low volume	-1/1	-0,97/1	-0,93/1	-0,93/1	-0,84/1	-
	Big/small part size	-1/1	-0,97/1	-0,93/1	-0,93/1	-0,84/1	-
	Other materials/0	-1/0 (Plastics)	-1/0 (Plastics)	-1/0 (Plastics, metals)	-1/0 (Plastics, metals)	-1/0 (Plastics, metals, ceramics)	-1/0 (Plastics, metals, ceramics, glass)
	-	-	-	-	Apply GII score	-	-

4.1.6 Section summary

In this subchapter, various scenarios for the year 2035 with different future developments in 3DP are described. These developments will improve 3D printers in the future, making them more capable of dealing with product characteristics that are deemed unfavourable today. The 3D Competitiveness Score Model will change, which in turn will influence the decentralization levels for these products. The 3D Competitiveness Score Model adapted to the five future scenarios are shown in Table 4-1.

4.2 Future maritime containerized transport

The globalisation of production and trade in the past decades has led to highly interlinked and complex trade routes. In this subchapter, we take a look at the current trends in the international seaborne trade and the container trade flows (Section 4.2.1). The goal is to gain insight of the commodity flows (Section 4.2.2) and how decentralization of the supply chain impacts these flows (Section 4.2.3).

4.2.1 Global maritime containerized trade today

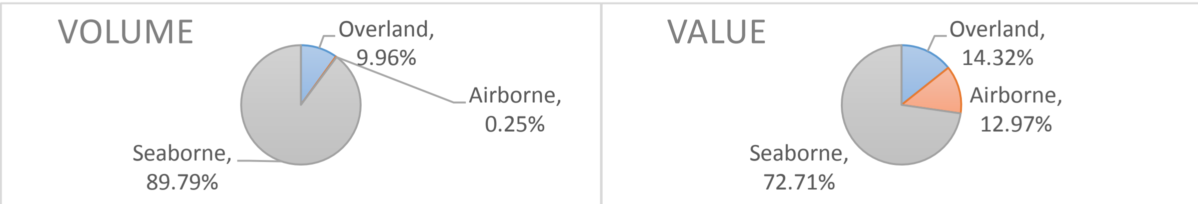


Figure 4-1 Modal share of world trade by volume and value (HIS Global Insight, Inc., 2008, cited in Rodrigue, 2013)

Most of the international trade today still happens overseas. 89,8% in volume and 72,7% in value of the world trade in 2008 (not including intra-EU trade) was seaborne (Figure 4-1). While airplanes only carry 0,25% of all the tonnage, it represents almost 13% of the total value. Maritime shipping is mostly used for goods of lower value, such as bulk minerals. However, containers (e.g. retail goods) and oil are still shipped over sea, which are considered high value goods (Rodrigue, 2013a). Global seaborne trade has grown 3% on average every year since 1970, reaching about 8,7 billion tons in 2011 (Figure 4-2). 15,6% of which consists of 20-foot equivalent unit (TEU) containers (1,4 billion tons). The 1,4 billion tons of TEUs in 2011 is equivalent to 151 million TEUs (Clarkson Research Services, cited by UNCTAD, 2012).

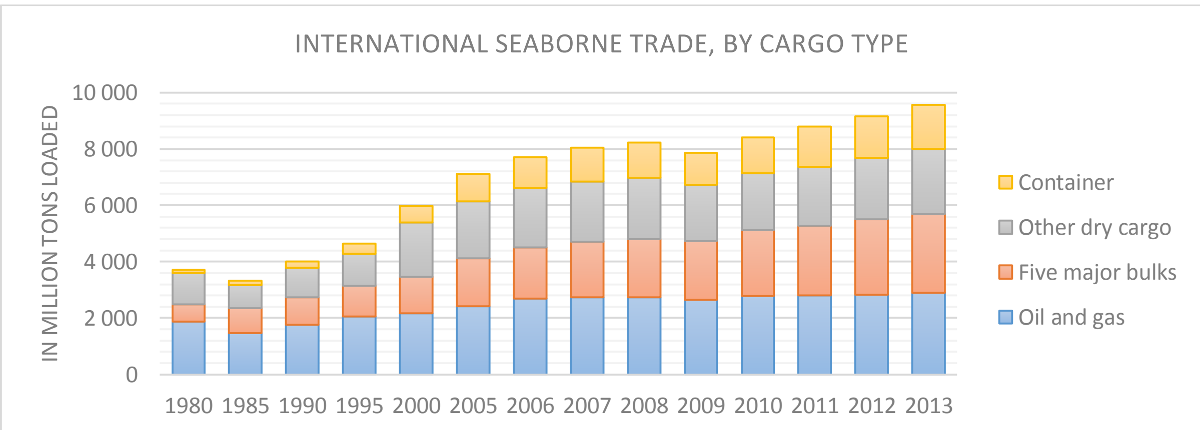


Figure 4-2 International seaborne trade, by cargo type, in millions of tons loaded (UNCTAD, 2013)

The global seaborne containerized trade grew 4,6% to 160 million TEUs in 2013 (UNCTAD, 2013). Three major trade routes connect the three main economic regions, namely the **Transpacific, Europe**

Asia, and **Transatlantic** trade lanes. Asia (the manufacturing centre of the world), Europe and North America (the major consumption markets) account for almost 80% of the world GDP in 2012 (UNCTAD, 2013). The total cargo flow on these trade routes sums up to 48,3 million TEUs (30,2% of 160 million TEUs) (UNCTAD, 2014). The volumes of the containers flow between these regions are shown in Figure 4-3.

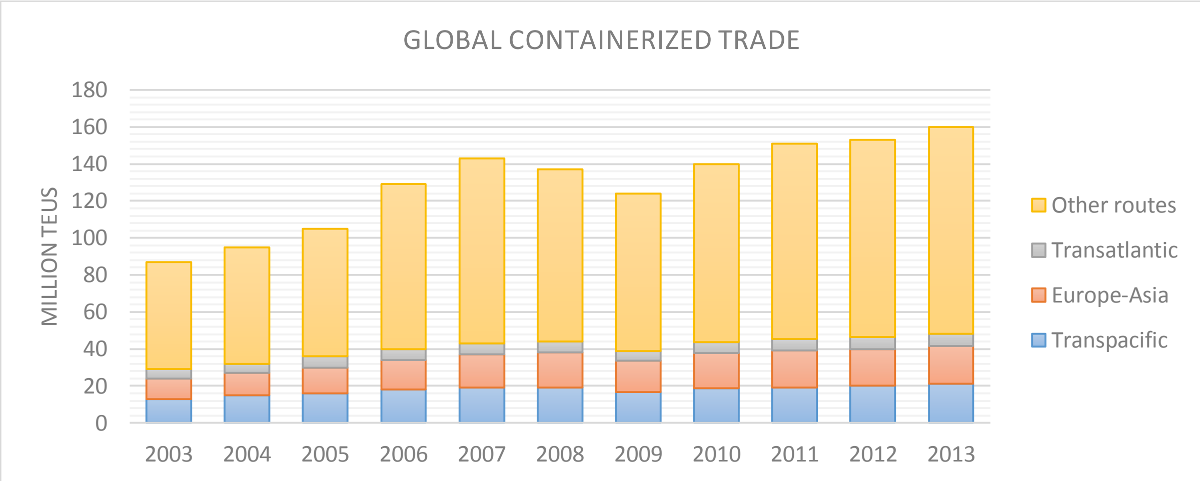


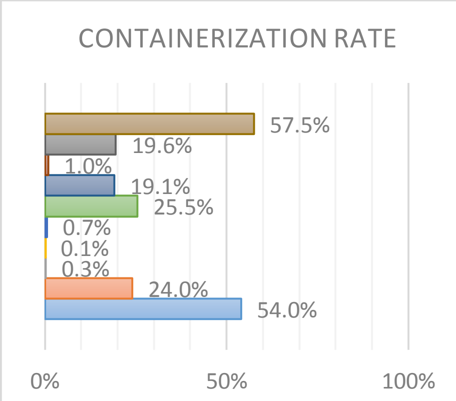
Figure 4-3 (Left) Global containerized trade, in million TEUs (UNCTAD, 2014; UNCTAD, 2013; UNCTAD, 2012; UNCTAD, 2011; UNCTAD, 2010)

4.2.2 Containerization per NSTR product group

The Nomenclature uniforme des marchandises pour les Statistiques de Transport, Revisée (NSTR) system is the standard classification system used by the EU since 1967 (CBS, 2013) and it is also used in the WCM. It categorizes all traded products in 10 groups. These are:

- **NSTR 0: Agricultural products and live animals** (e.g. cereals, potatoes, cattle)
- **NSTR 1: Foodstuffs and animal fodder** (e.g. sugar, coffee, meat)
- **NSTR 2: Solid mineral fuels** (e.g. coal, cokes, peat)
- **NSTR 3: Petroleum products** (e.g. crude petroleum, kerosene, energy gas)
- **NSTR 4: Ores and metal waste** (e.g. iron ore, steel waste, ore residues)
- **NSTR 5: Metal products** (e.g. rails, plate steel, semi-manufactured steel products)
- **NSTR 6: Crude and manufactured minerals, building materials** (e.g. sand, salt, cement)
- **NSTR 7: Fertilizers** (e.g. natural sodium nitrate, potassic fertilizers, phosphathic slag)
- **NSTR 8: Chemicals** (e.g. suphuric acid, wastepaper, perfumery)
- **NSTR 9: Machinery, transport equipment, manufactured and miscellaneous articles**

We are mainly interested in the container flow in terms of units per NSTR group, however most databases only list the number of tons per NSTR group. Thus these number need to be converted. To accomplish this, the containerization rate and the average weight per containerized NSTR will be used (Figure 4-4). **Containerization rate** is the share of the total weight of a NSTR group transported using containers (detailed in Appendix M).



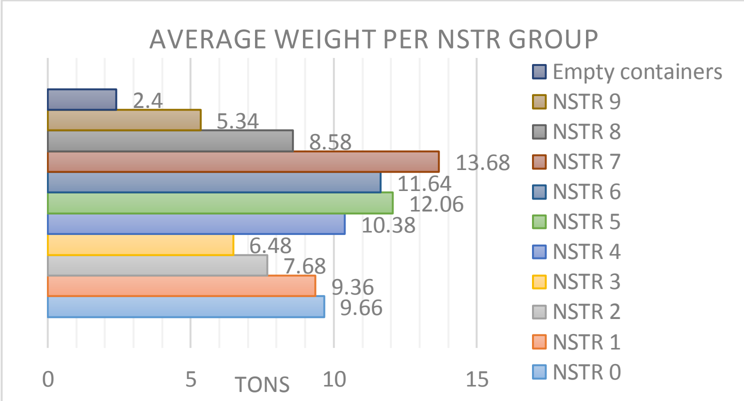


Figure 4-4 (Left) Containerization rate of imported NSTR products of the total weight in the Netherlands in April 2007 (CBS, 2007)
Figure 4-5 (Right) Average weight of a containerized NSTR products per TEU excluding the container weight (CBS, 2008)

An example of conversion of tons to TEUs is shown in Table 4-2, an estimation of the share of TEUs per NSTR group imported and exported in EU28 in 2013. The total TEUs handled corresponds generally well with the real maritime container import and export (Eurostat, 2014a). These numbers are a result of multiplying the containerization rate (Figure 4-4) with the number of tons per NSTR group, divided by the average weight of the containerized product group (Figure 4-5).

Table 4-2 Estimated share of the total imported and exported TEUs per NSTR group in EU-28, 2013, based on Eurostat (2014b)

NSTR group	Tons (import-export)	Tons containerized	TEUs	% of TEUs
NSTR0	97 041 935	52 370 594	5 421 387	18.3%
NSTR1	113 609 151	27 294 044	2 916 030	9.9%
NSTR2	178 517 729	567 064	73 836	0.2%
NSTR3	724 477 559	707 244	109 143	0.4%
NSTR4	146 476 695	958 033	92 296	0.3%
NSTR5	65 579 814	16 716 232	1 386 089	4.7%
NSTR6	88 291 385	16 845 361	1 447 196	4.9%
NSTR7	23 778 873	237 339	17 349	0.1%
NSTR8	103 307 752	20 203 848	2 354 761	8.0%
NSTR9	146 125 544	84 025 679	15 735 146	53.2%
Total	1 690 249 779	219 925 439	29 553 233	100.0%

4.2.3 Relationship between decentralization level and container flow

As concluded in chapter 3, decentralized manufacturing (DM) leads to reduction of transport on the manufacturer-consumer side, and an increase of transport on the supplier-manufacturer side. It is assumed the manufacturer-consumer side mainly comprises NSTR 9 transport flow, as it is the group with manufactured products (final goods). Also it is assumed the supplier-manufacturer side mainly comprises the other NSTR groups, as those comprises mainly raw materials and half fabricates. Following this reasoning, decentralization of manufacturing will result in a decrease of maritime transport volume for the NSTR 9 group, as the transport on the manufacturer-consumer side will be replaced by road or 3DP at home. While on the other side (supplier-manufacturer), this decrease will be replaced by the same volume of goods transported for the materials used to build NSTR 9 products (i.e. NSTR 0-8).

It will be assumed the decentralization level equates to the percentage of transport volume reduction in tons. The amount of transport volume reduction from NSTR 9 group, will be added to the transport volume of raw materials (NSTR 0-8) plus 10% to include material waste during production. By looking at the primary raw material composition of the NSTR 9 subgroups, the allocation of NSTR 9 transport volume to other NSTR groups can be assumed. Table 4-3 shows the assumed primary raw material composition of NSTR 9 subgroups, and the NSTR groups in which these raw materials belong.

Table 4-3 Allocation of NSTR 9 products transport volume to other NSTR groups based on their primary raw material composition. Product groups with unknown primary raw material composition are allocated to other NSTR groups of other subgroups.

NSTR 9		Description	Primary raw material	Supplying NSTR group
91		**Transportation equipment**		
	910	Transport equipment, whether or not assembled parts thereof	Metals	NSTR 5
92		**Agricultural tracts and machinery**		
	920	Agricultural tracts and equipment, whether or not assembled parts thereof	Metals	NSTR 5
93		**Electric and other machinery, apparatus**		
	931	Electric machinery, apparatus, engines	Metals	NSTR 5
	939	Non-electric machinery, apparatus	Metals	NSTR 5
94		**Manufactures of material**		
	941	Finished structural parts of metal	Metals	NSTR 5
	949	Other manufactures of metal	Metals	NSTR 5
95		**Glass, glassware and ceramic products**		
	951	Glass	Sand	NSTR 6
	952	Glassware, pottery, and other manufactures of minerals	Sand	NSTR 6
96		**Leather, textiles and garments**		
	961	Leather and furs	Animal skin	NSTR 0
	962	Textile yarn, fabrics, made-up articles and related products	Natural fibre	NSTR 0
	963	Clothing and footwear	Natural fibre	NSTR 0
97		**Other finished and semi manufactured products**		
	971	Finished and semi manufactured rubber products	Natural rubber	NSTR 0
	972	Paper and cardboard	Cellulose	NSTR 8
	973	Paper and cardboard manufactures	Cellulose	NSTR 8
	974	Paper matter	Cellulose	NSTR 8
	975	Furniture, new	Wood	NSTR 0
	976	Wood and cork manufactures, excluding furniture	Wood	NSTR 0
	979	Other manufactured articles	Unknown	NSTR 0 & 8
99		**Miscellaneous articles**		
	991	Packing containers, used	Cellulose	NSTR 8
	992	Construction materials, used	Metals	NSTR 5
	993	Removal equipment	Metals	NSTR 5
	994	Pearls, precious stones, precious metals (gold), coins	Metals	NSTR 5
	999	Other manufactured goods	Unknown	NSTR 5 & 8

4.3 Modelling the future using the World Container Model

The World Container Model (WCM), developed by TNO in partnership with Delft University of Technology and TML, models the global container flows between most ports in the world. It is the most comprehensive in terms of variables and statistics used. It combines a consistent description of worldwide trade flows, container flows and transportation services on a global scale, combined with a port and multimodal route choice model. The WCM will form the basis for assessing the impact of 3DP on future container transport. In this section, how the WCM works (Section 4.3.1) and how the future input data for the WCM is compiled (Section 4.3.2) will be explained.

4.3.1 How the World Container Model works

The WCM uses an extensive set of input data, such as the country-based origin/destination (O/D) matrix of TEU trade between 236 countries per NSTR product category, global maritime and service networks including 436 ports and their capacities, and 849 maritime container liners. Figure 4-6 shows an overview of the current version of WCM. For a detailed explanation, refer to Tavasszy et.al (2011) or Van Diepen (2011).

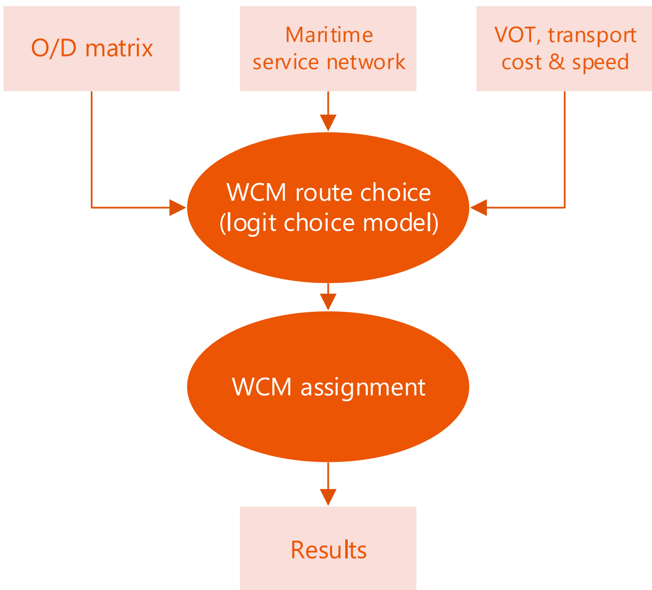


Figure 4-6 The World Container Model (Tavasszy, Minderhoud, Perrin, & Notteboom, 2011)

Origin/destination matrix

The WCM uses the zonal data from the United Nations (Classification ISO ALPHA 3) comprising 236 countries. The O/D matrix lists the TEU trade per NSTR group between all countries based on 2006 data compiled from different sources. The data has been calibrated against all available port throughput statistics.

Maritime service network

Each country is considered a zone represented by a centroid located at the capital, assuming it represents the economic centre of a country. 437 ports are represented by port nodes on locations of existing ports. Service providers is listed including their frequencies, transit times, speed and number of ships. The hinterland network is simplified to a link with fixed cost and speed between the port and the country.

VOT, transport cost & speed

Value of Time (VOT) in passenger transport is the opportunity cost of a traveller during his journey. In freight transport, VOT is a complex matter as the decision maker is not the transported product, but is determined by different actors (e.g. freight owner, shipper) each with their own VOTs. In simplest terms, it represents the average trade-off for decision makers between faster (i.e. more expensive) or cheaper (i.e. slower) transport options. An average of 73 USD is applied to all commodities.

An average value is used for transport cost, which comprises continental (road) transport cost (0.57 USD/TEU/km), maritime transport cost (0.025 USD/TEU/km), and transfer cost (0 USD). Transport speed is calculated for each service separately or a default of 1000 km/day is applied.

Route choice model

The WCM uses a simple logit choice model to compute a route and port choice, based on the assumption that shippers aim for profit maximization while knowing all the route alternatives. The logit model has been extended with a path size logit model to incorporate route overlaps. Refer to Appendix N for the formulas.

The choice set routes are determined by a shortest path algorithm for every port pair of the service. Choice sets are generated for every O/D pair. A route between two ports is defined by one or more maritime services with potential transhipments between services.

Assignment

Once the routes are generated, the trade flows are being assigned to the network using the logit route choice probabilities. Neighbouring countries are also considered in the logit route choice.

4.3.2 Future input data and base scenario

Van Diepen's (2011)'s future base (2040) O/D matrix will be used as the 2035 base scenario. To compile the base future O/D matrix, he used the gravity model (Appendix N), which is a common tool used for forecasting global trade. It predicts the bilateral trade flows based on economic mass (often determined by GDP) and the (relative weighted) distance between countries. The parameters were derived from the dataset from De Groot, Linders, Rietveld, & Subramanian's (2004) work. The model was applied on the 2010 data using the GDP level and population level of that time, and calibrated using the UN Comtrade data of 2010. The same method has been applied for the 2040 O/D matrix using the GDP growth rates (Appendix L, based on Cobb Douglas' GDP growth function) and population projections (based on HSBC's (2012) projections). Ideally a 2035 O/D matrix is compiled.

Due to time constraint, it has been opted to use Van Diepen's work as the time frame corresponds reasonably well (only 5 year difference). And also to compile a 2035 O/D matrix using the gravity model will require a revision of 11869 relations for each of the ten commodities, which will take considerable amount of time for only a slight improvement of data accuracy. The other option to compile a 2035 O/D matrix is to use a country's forecasted GDP growth rate applied as a growth factor to the outgoing container flow of that country. This method can be done fairly quickly, however this not a realistic assumption as trade flows depend on both the importing and exporting nation's GDP (De Groot, Linders, Rietveld, & Subramanian, 2004).

The input data VOT, transport cost & speed, maritime links, and port calibration data, are assumed to remain constant. Figure 4-7 shows a flowchart with all the steps of how the future O/D matrices are compiled.

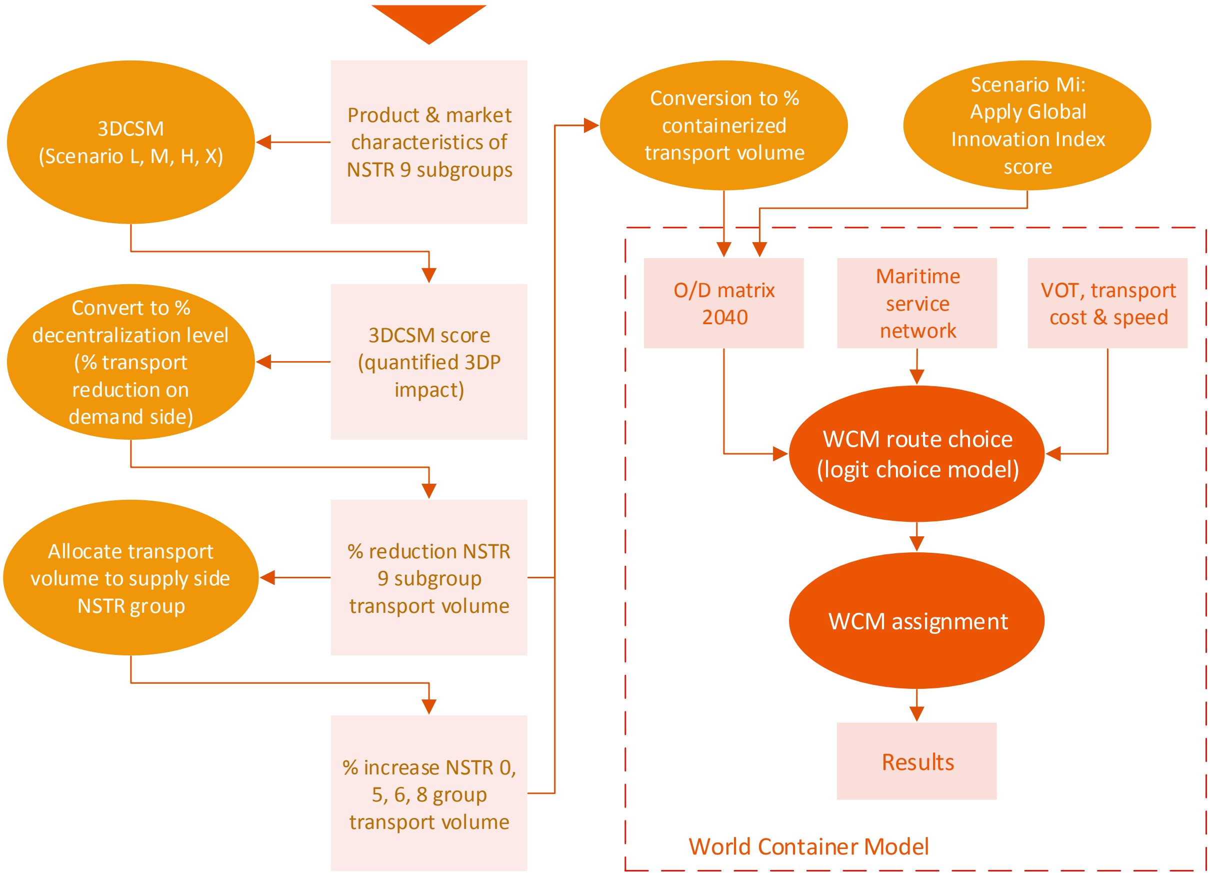


Figure 4-7 Flowchart showing the all steps to compile the future O/D matrix

4.4 Section summary

In this chapter, the methodology to model the future world container flow with 3DP impact is described.

Section 4.1 describes the different future scenarios.

- Future 3DP adoption mainly depends on the technological progress in the next decades. Improvements should reduce the technological barriers found in 3DP processes today.
- Five 2035 scenarios have been proposed, scenario L with a low technological advancement rate, scenario M with medium technological advancement rate, scenario H with high advancement rate, scenario Mi incorporates the Global Innovation Index, and scenario X with an extreme high advancement rate to test the upper bound of the 3DP impact.
- Each scenario alters the 3DCSM differently, thus producing different scores and decentralization levels.

Section 4.2 examines the current trends in the international maritime transport and explains how decentralization of the supply chain impacts different commodity flows.

- Seaborne trade remains the top in terms of freight volume and value transported. Current total TEU trade comprises 160 million TEUs. The Transpacific, Europe Asia, and Transatlantic are the most prominent trade lanes.
- Due to a lack of data on container trade per NSTR product group, the data (usually in tons) need to be converted using the containerization rate and the average weight per TEU.
- It is assumed decentralization results in the decrease of NSTR 9 transport volume (final products), and increase of transport volume of NSTR products that are deemed NSTR 9's raw materials. The raw material composition of NSTR 9 subgroups has been shown and linked to the supplying NSTR.

Section 4.3 explains how the World Container Model works and how the input data for future scenarios is compiled to be used in the WCM.

- The WCM uses an improved logit choice model to compute container flows and port throughputs. The O/D matrix with TEU flows between each country, maritime service network, VOT and transport cost & speed are its input data.
- The future base (2040) O/D matrix compiled by Van Diepen using a gravity model will be used as our 2035 base scenario. This is a less accurate but more time saving method than compiling the 2035 base scenario using the gravity model.
- How the O/D matrix per scenario is compiled is shown in a flowchart. Other input data, e.g. VOT, are assumed to remain constant.

Key assumptions

- Decentralization level equates to the percentage transport volume reduction of NSTR 9, and allocation of that transport volume to other NSTR groups.
- The primary raw material composition of NSTR 9 subgroups determines the allocation of transport volume to the corresponding NSTR group.
- VOT, transport cost & speed, maritime links, and port calibration data, are assumed to remain constant

Chapter 5

Results from the World Container Model

"Some writers and people who talk about 3D printing get over-enthused…a lot of that stuff is definitely hype and won't happen."

Charles Hull, co-founder of 3D Systems, 2013

In the previous chapter, scenarios have been compiled and it is explained how the input data has been modified for the World Container Model. In this chapter, the results from the WCM will be presented. It should give the final answer on how the 3DP technology will impact the world container transport. It the technology currently overhyped or does it have its proclaimed disruptive power? Section 5.1 elaborates on the port throughput and Section 5.2 on the port tot port container flows. Extended throughput and port to port flows can be viewed in Appendix Q. Screenshots of the generated container flows and port throughputs can be viewed in Appendix Q.

5.1 Port throughput

In this section, the results from WCM in terms of port throughput are presented. Section 5.1.1 shows the global port throughput and Section 5.1.2 shows the port throughput of top 10 ports. Section 5.1.3 shows the top 20 rankings of ports in terms of throughput in different scenarios. The extended results can be viewed in Appendix Q.

5.1.1 Global port throughput

The total throughput for all countries increases to above 231% for all future scenarios (Figure 5-1) from 2006, with less increase seen in higher 3DP advancement rate scenarios. Less difference is seen for Sc. L, M, Mi, and H compared to 2006 global throughput, ranging between a growth of 269% to 267%. Compared to the base 2035 future (Figure 5-2), again the Sc. X is the most notable with a total decrease of 10,2%. Other scenarios range between a difference of 0,297% and 0,583% compared to 2035 base.

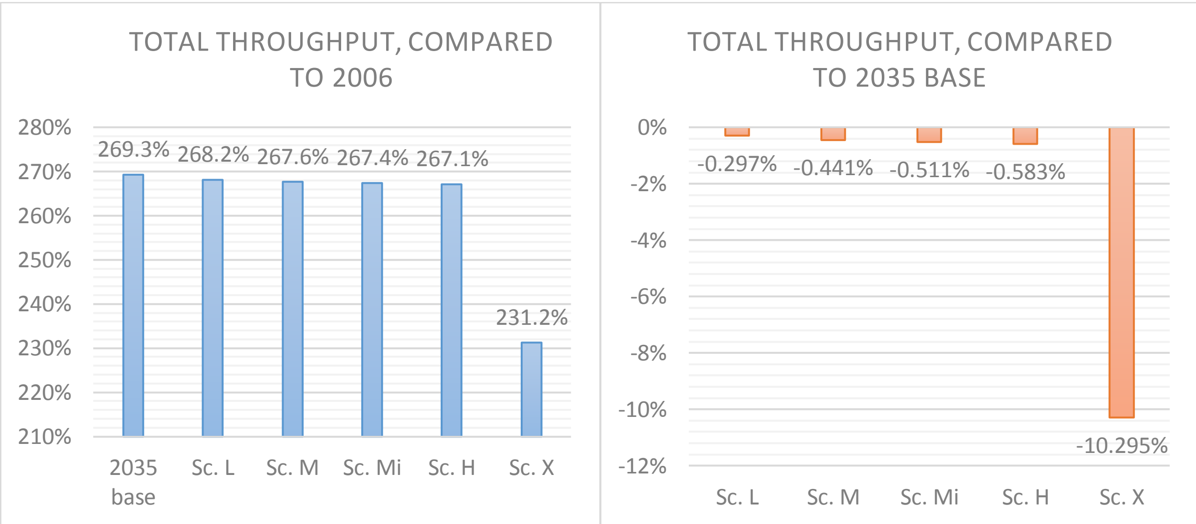


Figure 5-1 (Left) Total throughput, compared to 2006
Figure 5-2 (Right) Total throughput, compared to 2035

5.1.2 Top 10 ports with highest throughput

Also for the top 10 ports with highest throughputs (Figure 5-3), relatively small change from the 2035 base is observed for the scenarios L, M, Mi, and H. Again Sc. X seems to divert the most from the other scenarios. When comparing the 3DP impacted scenarios with 2035 base (Figure 5-4), the largest change is observed for the port of Long Beach with almost 22% less throughput for Sc. X, and the least change for the port of Antwerp with 7% less throughput. For other scenarios, the difference from 2035 base is relative small, with highest from Long Beach with -1,1%. For the Port of Rotterdam, 15% less throughput is observed for the extreme scenario. For other scenarios a decrease ranging between 0,85% and 0,44% is observed.

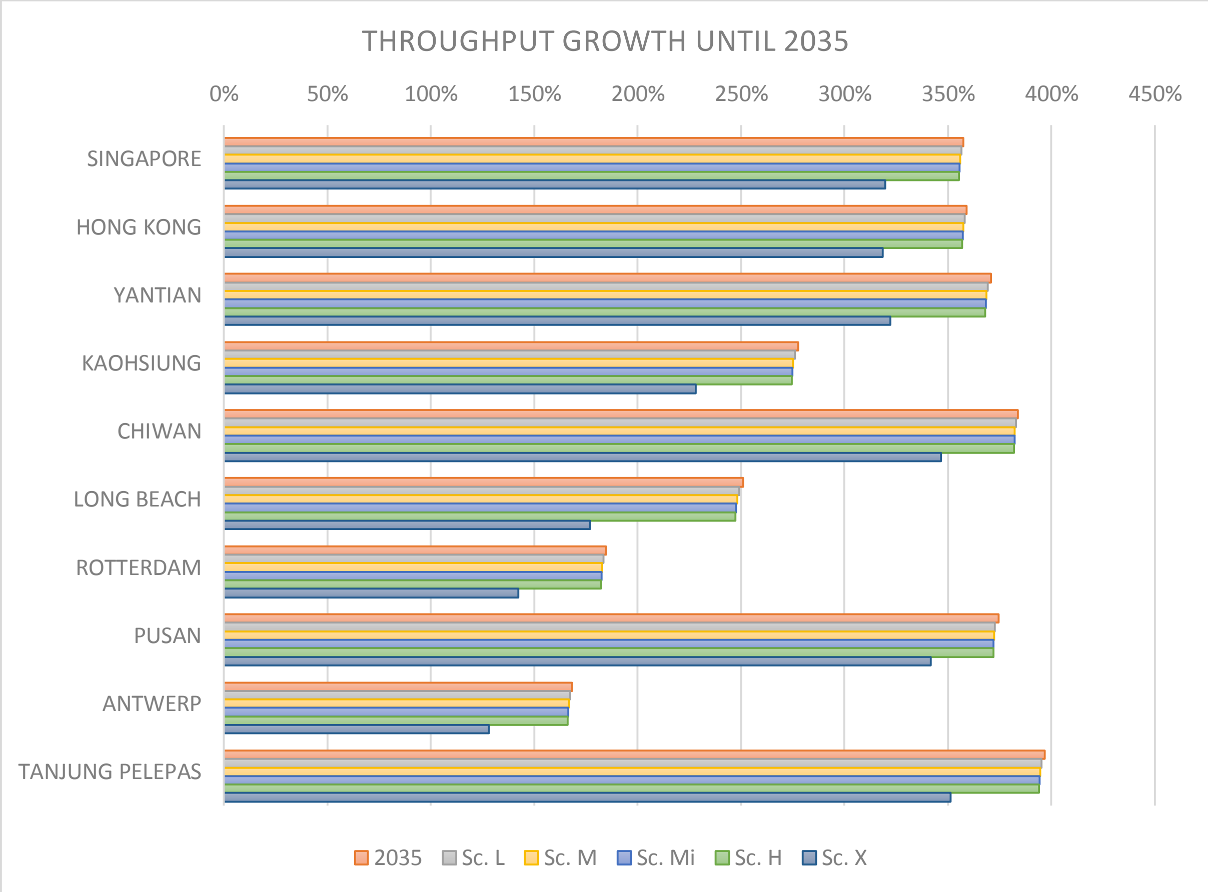


Figure 5-3 Throughput growth until 2035 from 2006

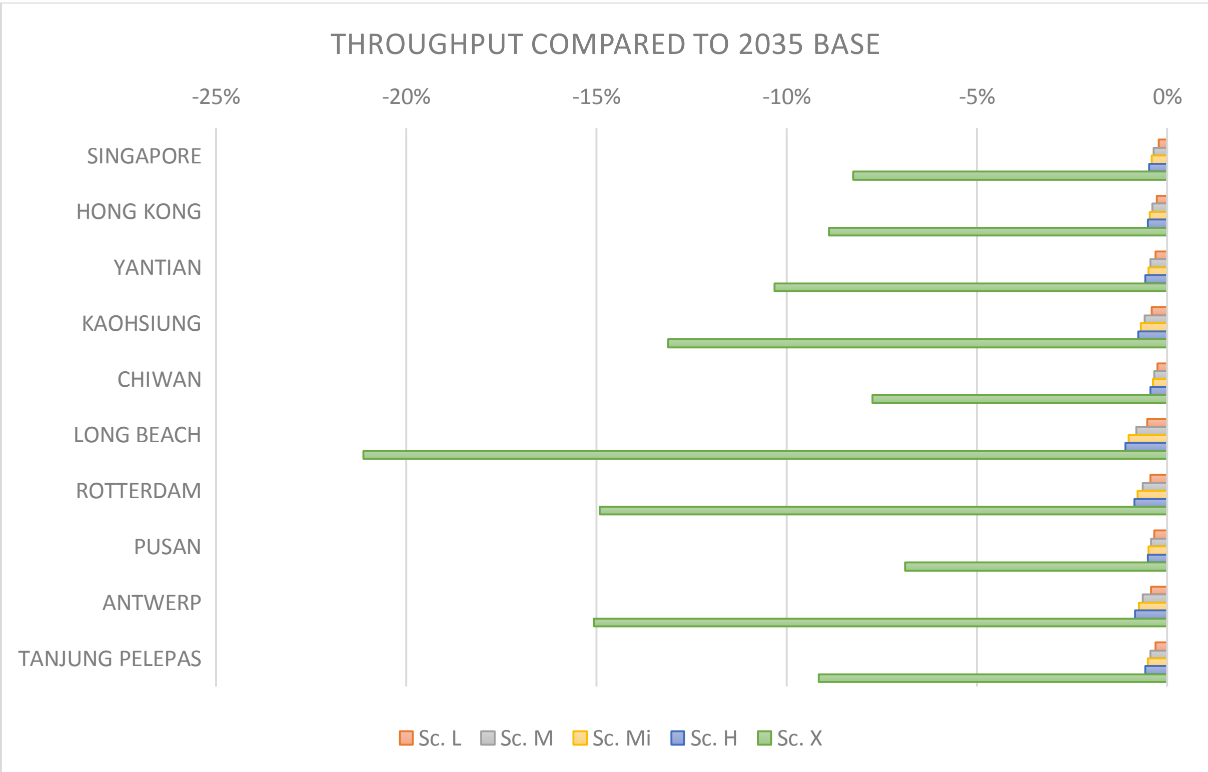


Figure 5-4 Throughput growth compared to 2035

5.1.3 Top 20 ranking by throughput

Table 5-1 Top 20 ports with highest throughput

Rank	2035 base	Sc. L	Sc. M	Sc. Mi	Sc. H	Sc. X
1	SINGAPORE	SINGAPORE	SINGAPORE	SINGAPORE	SINGAPORE	SINGAPORE
2	HONG KONG	HONG KONG	HONG KONG	HONG KONG	HONG KONG	HONG KONG
3	YANTIAN	YANTIAN	YANTIAN	YANTIAN	YANTIAN	YANTIAN
4	CHIWAN	CHIWAN	CHIWAN	CHIWAN	CHIWAN	CHIWAN
5	KAOHSIUNG	KAOHSIUNG	KAOHSIUNG	KAOHSIUNG	KAOHSIUNG	PUSAN
6	PUSAN	PUSAN	PUSAN	PUSAN	PUSAN	KAOHSIUNG
7	TANJUNG PELEPAS	TANJUNG PELEPAS	TANJUNG PELEPAS	TANJUNG PELEPAS	TANJUNG PELEPAS	TANJUNG PELEPAS
8	LONG BEACH	LONG BEACH	LONG BEACH	LONG BEACH	LONG BEACH	NANSHA
9	NANSHA	NANSHA	NANSHA	NANSHA	NANSHA	LONG BEACH
10	ROTTERDAM	ROTTERDAM	ROTTERDAM	ROTTERDAM	ROTTERDAM	SURABAYA
11	SURABAYA	SURABAYA	SURABAYA	SURABAYA	SURABAYA	ROTTERDAM
12	XIAMEN	XIAMEN	XIAMEN	XIAMEN	XIAMEN	XIAMEN
13	LAEM CHABANG	LAEM CHABANG	LAEM CHABANG	LAEM CHABANG	LAEM CHABANG	LAEM CHABANG
14	SHANGHAI	SHANGHAI	SHANGHAI	SHANGHAI	SHANGHAI	DUBAI
15	ANTWERP	ANTWERP	ANTWERP	ANTWERP	ANTWERP	SHANGHAI
16	DUBAI	DUBAI	DUBAI	DUBAI	DUBAI	SHEKOU
17	SHEKOU	SHEKOU	SHEKOU	SHEKOU	SHEKOU	ANTWERP
18	KOBE	KOBE	KOBE	KOBE	KOBE	KOBE
19	HAMBURG	HAMBURG	HAMBURG	HAMBURG	HAMBURG	BRISBANE
20	BRISBANE	BRISBANE	BRISBANE	BRISBANE	BRISBANE	CHENNAI

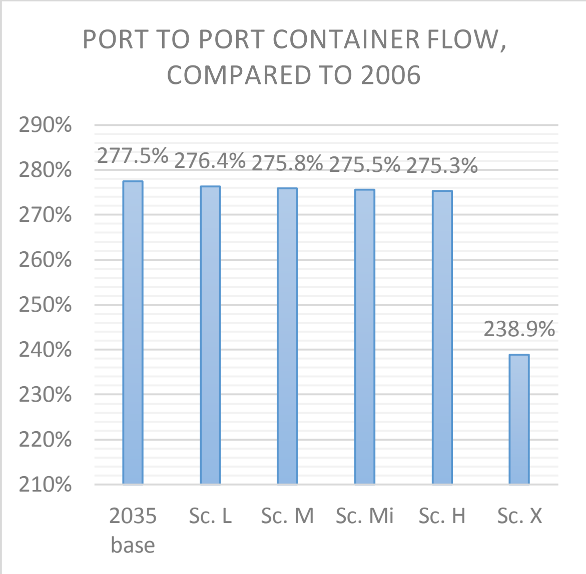
The top 20 ports with the highest throughput are shown in the table below for each scenario. The results show that in most scenarios the ranking stay relatively the same, with all ports decreasing in throughput with higher 3DP advancement rates. Only in Sc. X the changes are significant enough to change the rankings. The first four ports seem unaffected. The ports in lower position drop or rise two or three place at most. Rotterdam drops down one place in the extreme scenario.

5.2 Port to port container flows

In this section, the results from WCM in terms of port to port container flow in TEUs are presented. Section 5.2.1 shows the global container flow in TEUs and Section 5.2.2 shows the largest flows between ports. The extended results can be viewed in Appendix Q.

5.2.1 Global container flows

The global container flow increases at least 239% for all future scenarios (Figure 5-5) from 2006, with less increase seen in higher 3DP advancement rate scenarios. Also here, less difference is seen for Sc. L, M, Mi, and H compared to 2006 global container flow, ranging between a growth of 275% to 278%. Compared to the base 2035 future (Figure 5-6), the Sc. X shows a total decrease of 10,2%, while the other scenarios range between a decline of 0,299% and 0,583% compared to 2035 base. The percentage decline of global container flows is almost the same as the change in global throughput.



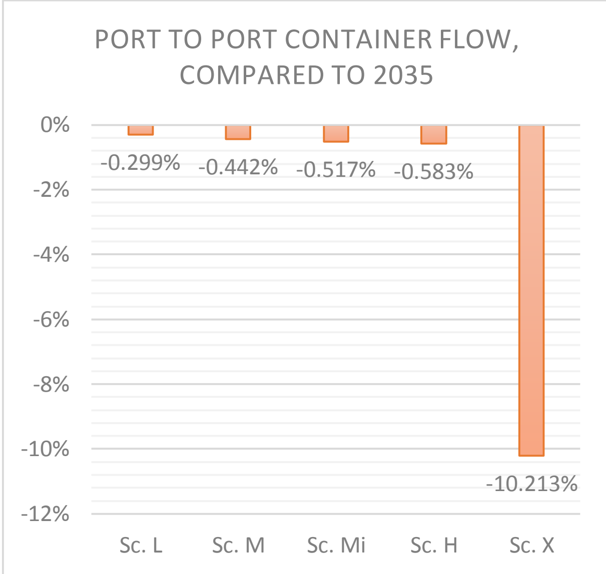


Figure 5-5 Port to port container flow, compared to 2006

Figure 5-6 Port to port container flow, compared to 2035 base

5.2.2 Top 10 port to port container flow

Figure 5-7 shows the largest flows between ports. The number are compared with 2006. Almost all flows show a high growth of around 400% until 2035, with an increase of 540% in container flow between Bandar Abbas and Port Klang. The only link to show a slight decline is Port of Rotterdam and Immingham.

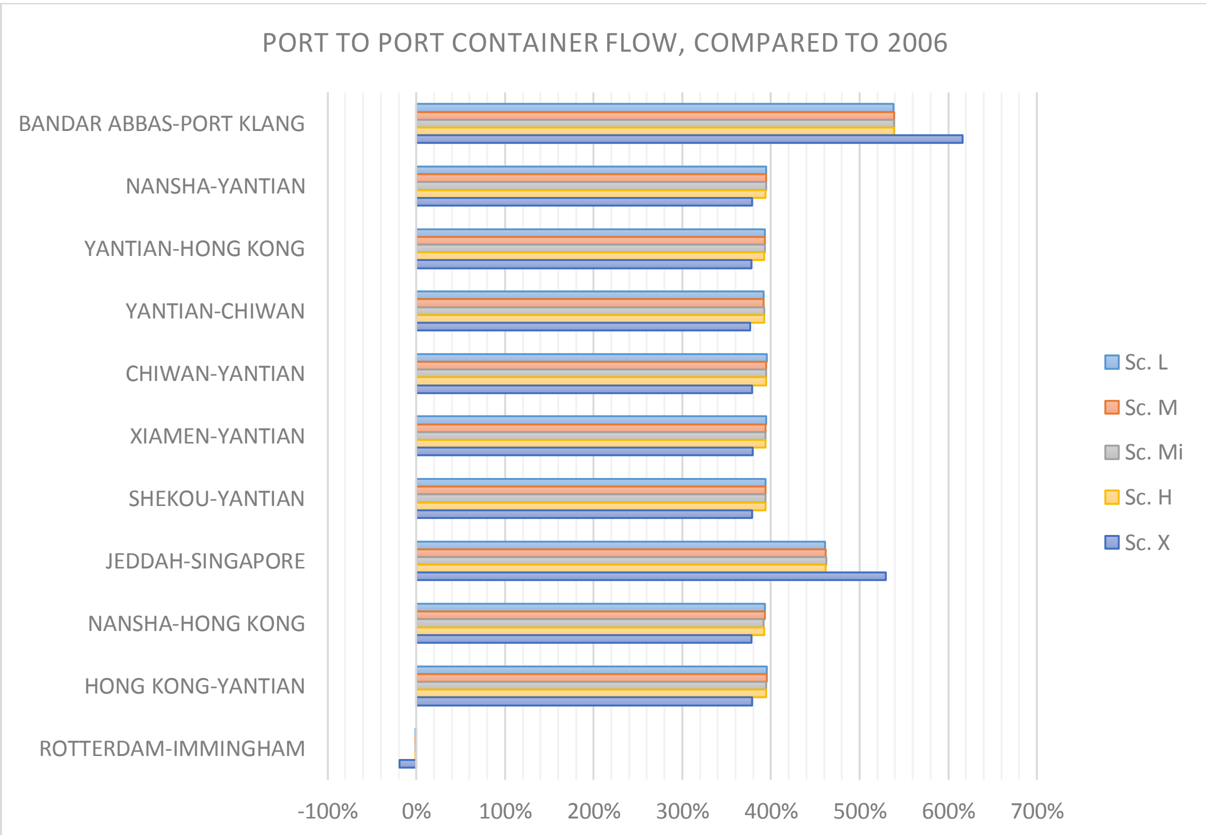


Figure 5-7 Port to port container flow, compared to 2006

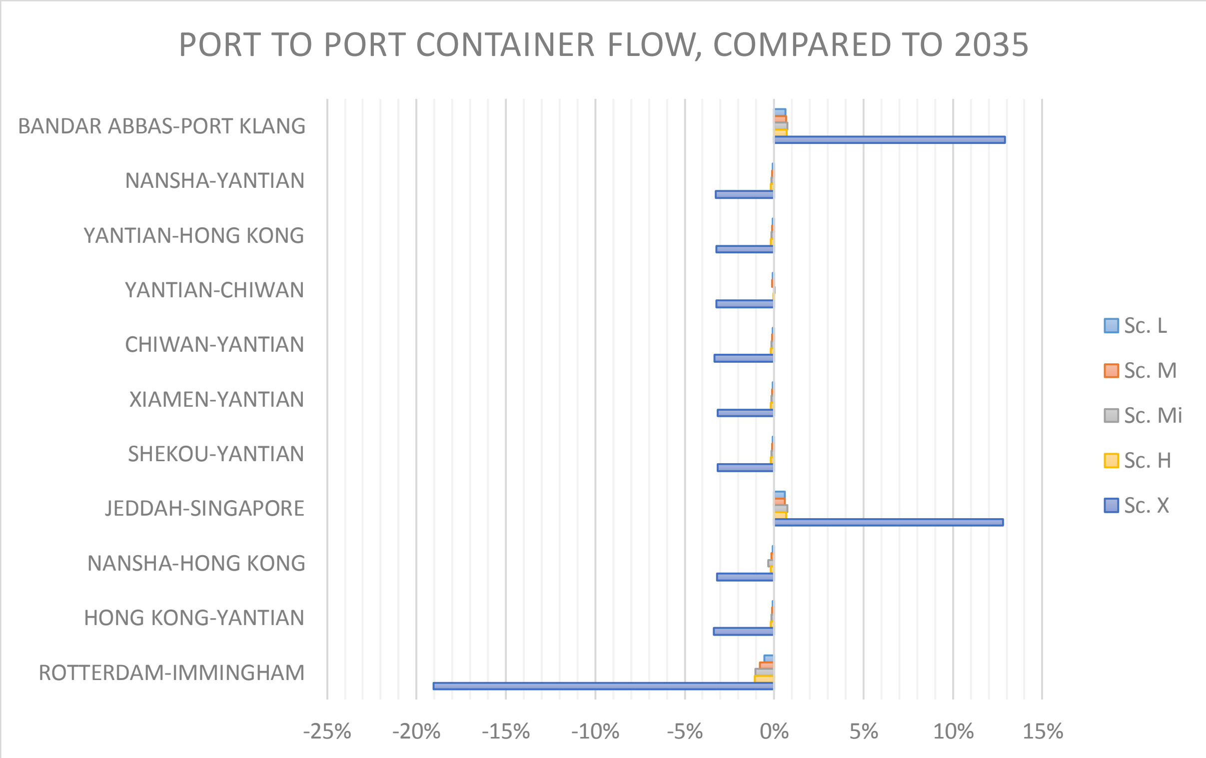


Figure 5-8 Port to port container flow, compared to 2035

Figure 5-8 shows the percentage change of port to port container flows compared to 2035. Interesting thing to note is, while most container flows decreases with increasing decentralization, some flows show an increase, namely the flow between Bangdar Abbas and Port Klang, and Jeddah and Singapore. This can be explained by the type of commodities that generally are been traded between these ports. It is possible Bangdar Abbas and Jeddah mainly export raw materials (NSTR 0-8). Due to the decentralization of NSTR 9 groups, it could be that the allocation of the NSTR 9 material to raw material transport stimulated a higher growth of this flow. Since Bardar and Jeddah are located in Middle-East, it could be that the allocation of plastic (raw material: petroleum) based NSTR 9 subgroups stimulated the extra growth of oil export. The flow between Port of Rotterdam and Immingham shows a decrease of 19% in the extreme scenario, and a decrease around 1% for other scenarios. Once again only Sc. X seems to be disruptive enough to change the rankings.

5.3 Section summary and conclusion

In this chapter, the results generated from the World Container Transport model has been presented and discussed.

In Section 5.2, the results show that 3DP impacts the global throughput in case of higher technological advancing rate. The impact of 3DP on the global throughput is generally insignificant. Due to the high forecasted growth of global trade, the most realistic scenarios present no risk of disruption, with a deviation from the base future throughput with less than a percent. Even in the extreme scenario, which includes a decentralization rate of almost 90% for many of the NSTR 9 goods, an event which is highly unlikely to happen within the next 20 years, the reduction in throughput growth is 10,3% max.

Most major ports remain at the top in terms of container handling. Realistically Port of Rotterdam may encounter a slightly less throughput (1%) due to 3DP impact.

In Section 5.2, the results show that 3DP also impacts the container flows between ports. In terms of percentage change from 2006 and 2035, the global container flow fall in line with the percentage change found in the global container throughput. Also here, the reduction in port to port container flows are less than a percentage compared to the future base, which is insignificant when considering the total growth to 2035 is above 230%. The largest flows between ports show that most links between the Asian ports will witness a high growth of around 400%. 3DP do not negatively impact all links, as some witness a growth with increased 3DP decentralization, namely two Middle-Eastern based ports. This could be explained by the focus of these ports in the export of raw materials, such as petroleum. The flow between Port of Rotterdam and Immingham, which was the largest flow in 2006 in terms of TEUs moved, shows a stagnation until 2035 and decline in case of the extreme scenario. The largest flows between ports however do not tell the whole story, as a port has many links.

Conclusion

In conclusion, 3DP poses no significant threat for the global maritime container transport. Container transport will experience a high growth until 2035 even with an extreme case of 3DP-inspired decentralization of manufacturing. The allocation of NSTR 9 (finished goods) to other NSTR groups will balance the reduction of transport need on the demand side with transport need on the supply side. A reduction in total transport flow or container throughput can be explained by the different containerization rates of NSTR groups. While manufactured goods are often found in containers, goods such as sand or oil are more often transported using bulk vessels. This means a smaller amount of material allocated from NSTR 9 group will end up in a container on the supply side transport.

As for the **ports**, if they have a particular focus on the handling of certain NSTR groups, due to their geographical closeness to the consumer market or raw material attraction/processing site, it is possible they will experience a slight shift in demand. It is more likely this will NOT be noticed by major ports as they are likely more diversified in terms of NSTR types handling, and thus they should experience a relatively small change that 3DP brings, especially combined with the high projected growth in the global container transport. Small ports that are generally less diversified, could experience noticeable change in demand.

For the **deep sea carriers**, it is possible they will witness a change in routes taken in 2035 compared to 2006. Instead of frequenting routes between the Western countries and developing countries, which is typical for today's globalized world with off-shoring as a standard manufacturing practice, it could be in 2035 they will frequent a more diversified shipping route. This is evidenced by the positive change of container flow between some links and negative change of container flow in other links, which suggests a change in the importance or attractiveness of different routes. This change is however still rather small according to the model results.

The **freight owners** is a large but highly fragmented stakeholder group in the organization of global transport. While they generally initiate the transport demand, they do not partake in the arrangement of freight transport themselves. In the future, if 3DP does decentralize many of the supply side manufacturing, it is possible freight owners of raw materials might notice an increase of smaller orders from multiple locations. This could lead to an increase of labour to arrange transport.

As for the **Port of Rotterdam**, it will remain in the top 11 largest ports in the world in terms of container throughput for the next 20 years. The port might experience a slight decline or stagnation in the container flow in several links until 2035, but as a diversified major port, this is likely compensated by an increase of transport flow on other links. In an extreme case of decentralization rate, this could be countered by a higher investment in bulk handling as raw material will likely become more transported NSTR group. Again, this is likely unnecessary when considering the relatively small 3DP impact on the global container transport.

Chapter 6

Conclusions and recommendations

The goal of this research was to analyse the impact of 3D printing technology on the world container transport. It is believed it is a disruptive technology for future manufacturing, supply chains and thus transport in general. The development of the technology and its potential has been extensively examined. Using this knowledge five scenarios were formed to be modelled in the World Container Model. With the results generated from the model, we are able to answer the main research question. The sub research questions provided a stepwise approach to answer the last and main question.

6.1.1 What are the current developments in the 3D printing sector?

3DP is still mostly in its infancy. Only basic plastic processes are at the most advanced level, ready for production implementation. High quality plastic and metal processes are halfway the MRL scale around the pre-production phase, while other material processes are still undergoing experiments. The market and its technical capabilities will surely grow steadily in the next decades. Several improvements can already be expected in terms process improvements, speed, quality control and materials for the coming decade.

6.1.2 What is the impact of 3D printing technology on manufacturing?

3DP provides manufacturing firms a unique set of attributes. As firms aim for increasing competitiveness, they will do so by upgrading their competitive capabilities. 3DP influences these capabilities differently (compared to conventional manufacturing) depending on the product that the firm makes and the market in which the firm operates. 3DP shows the most potential for increasing a firm's Time and Flexibility capability. 3DP allows a better Time capability as it provides faster development speed for innovative products and faster the delivery speed for customized products. It provides more Flexibility through easy customization, thus allowing more variety, and is more flexible in terms inventory management as it allows on-demand production for products with demand uncertainty. 3DP increases the Quality capability by increasing the performance through lightweighting, by providing more features such as ergonomics, increased serviceability for products that need maintenance/repair, and provides more design freedom and thus allowing an increased aesthetic performance. However 3DP can also decrease the Quality capability as the low process stability reduces the reliability of products, which is unacceptable for safety related products. Also the reproducibility is low, which means the conformance and durability of products can be reduced. 3DP can lower or increase the production cost depending on the production volume, part size, geometric complexity, and the material composition of a product.

6.1.3 What is the impact of 3D printing technology on supply chains and logistics?

The location of 3DP deployment impacts the supply chain and its logistics. Five types of 3DP deployment has been distinguished and it has been shown that only decentralized 3DP deployment impacts the supply chain, in the form of eliminating the need of transport on the demand side (manufacturer-consumer). As the total material flow in a network should remain unchanged, regardless of the supply chain setup, it could be assumed that going from a centralized to a decentralized manufacturing setup will replace the maritime transport on the demand side, with material transport of the raw material on the supply side. Case studies show that 3DP stimulates the decentralization of manufacturing.

6.1.4 Considering these factors, what is the impact of 3D printing on the world container transport in the next 20 years?

3DP is not likely to cause a threat, in the form of significant throughput or transport flow reduction, for the global container transport in the next two decades. As the GDP and world population is not likely to decline the next 50 years, the global trade will likely continue to generate a high global transport demand, including container transport. This partly neutralizes the threat of reduction in container transport demand. Any reduction will be masked by the stronger growth of container transport activity. As the containerization rate will likely continue also for raw materials, the allocation of NSTR 9 product transport to raw material NSTR group transport balances the reduction of transport need on the demand side.

Major ports will likely not notice any significant change in terms of container throughput nor container flow. Due to their size and diversity in terms of freight handling, the aggregate transport activity will not deviate enough to be noticed. Any realistic change due to 3DP is less than 1% compared to a future base without 3DP impact.

Deep sea carriers might notice a slight change in routes taken in the future compared to today, as there are slight changes in the importance or attractiveness of different routes. It is likely a more diversified routes are requested. However this is likely too small to be noticed.

Freight owners of raw materials might notice an increase of smaller orders from multiple locations due to the decentralized nature of manufacturers (their clients). This could lead to a slight increase of labour to arrange transport.

The Port of Rotterdam will remain among the top 11 of the largest ports in the world in terms of container throughput for the next 20 years. As said before, as a major port, the change of container flow in several links caused by 3DP is likely compensated by an increase of transport flow on other links, and the high global growth of container transport demand.

For the coming decades, it will likely continue to drive sales for "unique" products, which are low in volume and high in value. Economy of scale will likely never reach the same level of mass production. The analogy for the paper printer can be used. 65 years after the arrival of the first home digital printer, people still buy books, rather than printing them. Maybe after 50 years it could start to reduce the transport flow more significantly.

Recommendations

It has been concluded that 3DP in general does not cause any significant reduction of container transport that could negatively impact the stakeholders. Thus the following recommendations aim to accommodate extreme cases of 3DP impact or counter any (slight) 3DP impact.

Major ports:

By remaining diversified in types of freight handling, it will reduce the risk of having over- or under-capacity to accommodate sudden change of transport demand for a particular freight.

Deep sea carriers:

Localize service to Asian ports, as these ports are projected to have the strongest growth for the next 20 years.

Freight owners:

Consider cooperation with distribution centres for a more efficient fulfilment of smaller orders for possible smaller manufacturers in the future.

Port of Rotterdam:

As a major port, the same recommendation of diversification can be given.

Chapter 7

Reflection and further research

Score model and decentralization level

3D Competitiveness Score Model

The 3DCSM is a generic score model which might not fit certain firms, as some firms might have different dimensions that make up their competitive capability. Also different firms value the competitive capabilities differently, as some might focus on cost reduction and others on flexibility. This means, ideally different weights should be applied on each competitive capability per sector. A more extended market analyses and validation could have been done to make it more market specific and accurate.

Decentralization level in relation to the 3DCSM score

The fitted curve to formulate the relationship between 3DCSM score and decentralization level in a certain market is highly speculative due to the limited amount of data points. While the data points for the dental and hearing aids industries are more solid, the third data point (other industries) is uncertain and is a sensitive point. More market data is needed to assess the effect of 3DP market penetration in relation to the decentralization level. Also the 3DCSM score reflects the market potential, it does not reflect the market penetration. For simplicity, 3DCSM has been assumed to relate to the decentralization.

Allocation of demand-side transport volume to supply side

This assumption follows from the notion that the total material transport in a system must stay the same, regardless of a DM or CM structure. However material waste during production varies per industry and per product. And since 3DP is reported to be more material efficient, the total material flow through a DM structure could be less than that of a CM structure. Also it is possible the replaced material flow at the manufacturer-consumer side could be replaced by other modes, such as air transport.

World Container Model

Scenarios

The scenarios created could have included more factors, such as political, economic, social aspects. Instead, only the technical aspect of 3DP has been taken into account. Also the scenarios L, M, and H only vary slightly, which makes their range seem too narrow and are deemed redundant. However, this could only have been known in hindsight.

Input data

To compile the scenario O/D matrices, the decentralization level has been applied to the future O/D matrix in the form of subtraction and addition. This is less realistic as this would seem an advanced 3DP technology arrived all of a sudden in the future. It would have been better to incorporate the 3DP impact and decentralization level in a comprehensive gravity model to support a gradual distribution of the 3DP impact. This might be interesting for further research.

No calibration has been done to change the 2006 O/D matrix to current transport flows. A calibration would have made the comparison with today's transport activity more insightful. One noticeable port missing from the top 10 is the Port of Shanghai, which is currently the largest in the world in terms of container throughput.

Van Diepen's 2040 O/D matrix has been used as the 2035 future base scenario. This is less accurate as there is a five year different between the two times scopes. However, this decision was necessary due to time constraints. Also the calibration of the gravity model was done using transport data from 2010. Ideally, 2014 data should be used for a more accurate prediction.

VOT average value

The VOT used as input data had an average rate for all the ten commodity types. This is inaccurate as it will influence the route choice and modal choice. The current WCM cannot be run with the integration of different VOTs. To use different VOTs, the transport flows of only one commodity could be calculated. It would benefit future WCM to incorporate different VOT values.

Mode results

A more detailed analysis could have been performed on the model results. The analysis mostly concerned the top 10 or 20 ports in terms of throughput or container flows. Especially for the different container flows it would have been more insightful to include containers flows to other ports for the analysis of the Port of Rotterdam.

Sensitivity analysis

A sensitivity analysis could have been used to assess all the different values and conversions used in this study to show the critical assumptions. However, in a study in which even the extreme scenario seems to do almost no impact, it might not have been necessary.

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Appendix A Additive manufacturing processes

A.1 Material Extrusion

Fused Deposition Modelling (FDM) (Figure A-1), which has been rebranded by the open source community as Fused Filament Fabrication (FFF), can be described as drawing with a precise **hot glue gun**. FFF works by extruding material through a nozzle to create a cross section (a layer) of an object, then moving up vertically to repeat the process. The resistive heaters at the nozzle melts the plastic as it flows through the tip while printing. The extruded plastic then hardens immediately as it bonds to the lower layer. The quality of prints using this technique depends mostly on the layer height; the thinner the layer, the smoother the printed objects appear. The resolution ranges between 75 microns (slightly thinner than a sheet of copy paper) and 300 microns. FFF technology is common in desktop 3D printers and less expensive professional printers (THRE3D, 2014a).

A.2 Material Jetting

Material Jetting (Figure A-2) printers resemble much to the traditional (paper) laser printers. Here, the print head moves around the print area **jetting photopolymer** (light-reactive plastics) instead of ink. UV lights surrounding the print head pass over the jetted material on the build area and solidifies it in place to form a layer. With this process it is able to print using multiple materials in a single job. The materials can be selectively positioned during a print, and can even be combined during the process to create other material types. It is a commonly used technique for prototyping, due to its high resolution (down to 16 micron layer heights, almost unnoticeable to touch), and its ability to match the look, feel, and function of the final product (THRE3D, 2014b).

A.3 Binder Jetting

Binder Jetting (Figure A-3) (or Inkjet Powder Printing) works by spraying a **liquid binder onto a powder bed**, solidifying it into a layer. It resembles the inkjet paper printer, in which instead of ink is being jetted onto a layer of paper, it is binder being jetted onto a layer of power. After the layer has been hardened, an automated roller deposits a new layer of powder on top to repeat the process. Binder Jetting is often used for producing end-use products, as it offers full colour printing and has less noticeable layer definitions than other processes. This process has also been scaled up to print architectural structures as big as a room (THRE3D, 2014c).

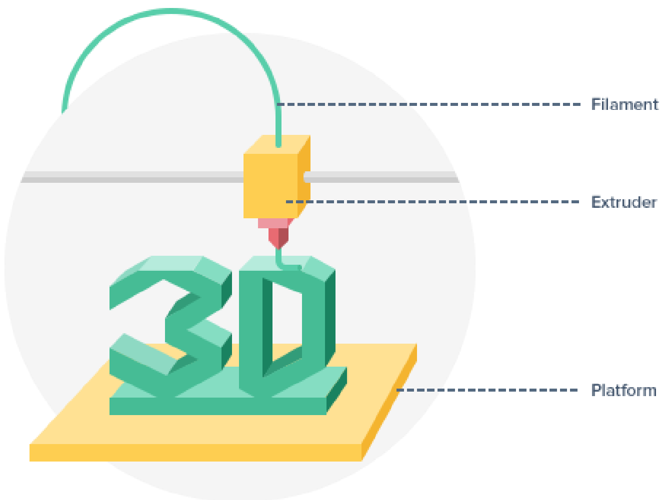


Figure A-1 Fused Deposition Modelling (FDM), or Fused Filament Fabrication (FFF) (THRE3D, 2014a)

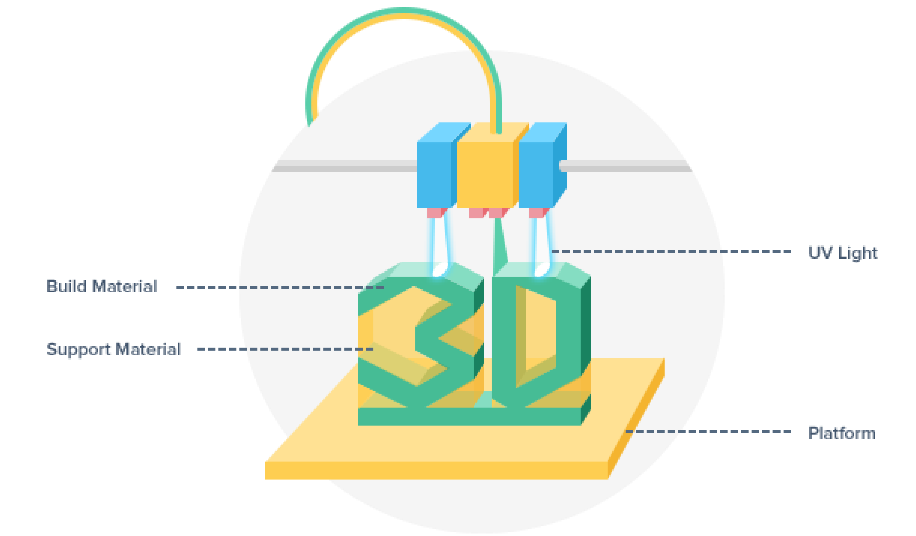


Figure A-2 Material Jetting (THRE3D, 2014b)

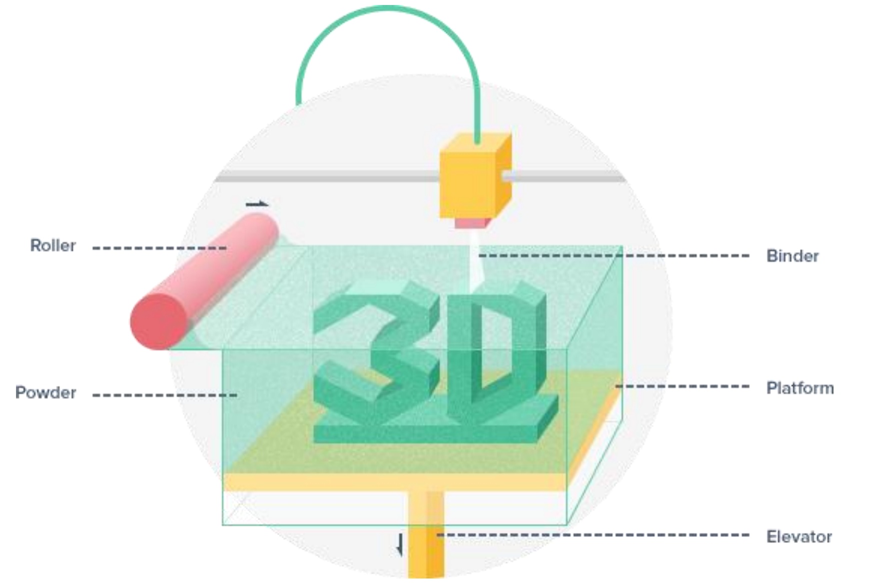


Figure A-3 Binder Jetting (THRE3D, 2014c)

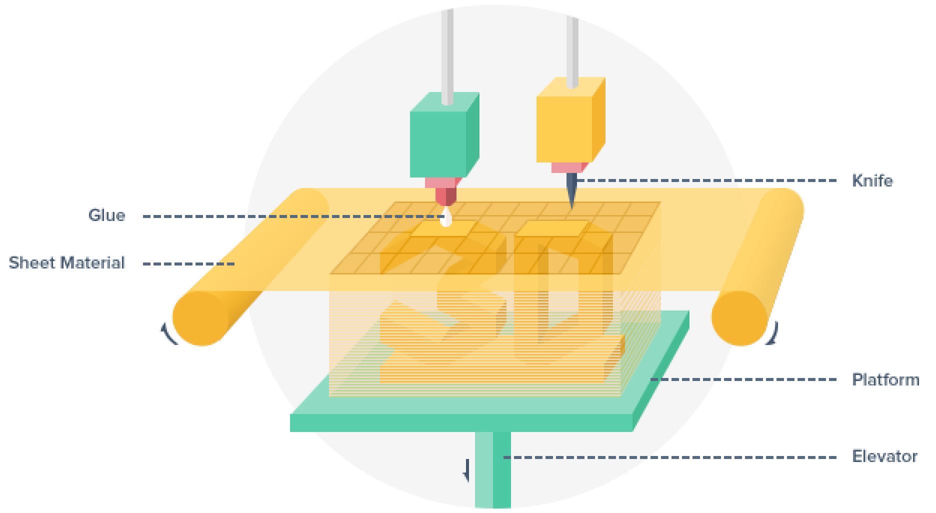


Figure A-4 Laminated Object Manufacturing (THRE3D, 2014d)

A.4 Sheet Lamination

Laminated Object Manufacturing (LOM) (Figure A-4) and Ultrasonic Additive Manufacturing are two types of sheet lamination processes. With Laminated Object Manufacturing, sheets of material are stacked and are bind together using glue. The printer then **slices an outline** of the object into a layer, of which the excess material will be removed later. LOM produces strong and durable products that generally show no distortion over time, which makes them suitable for all stages of the design cycle. The layer resolution is defined by the material feedstock and usually ranges in thickness from one to a few sheets of copy paper. Mcor's version of the technology makes LOM one of the few 3D printing processes that can produce prints in full colour (THRE3D, 2014d).

A.5 Vat Photopolymerization

Stereolithography (SLA) (Figure A-5) and Digital Light Processing (DLP) are two types of Vat Photopolymerization processes. With Stereolithography, a laser (beam of UV light) shines into **photopolymer resin**, causing it to react and become solid. The laser then draws the shape of the object cross section, forming a layer of hardened material. The hardened layer is then lowered into the resin so that the laser can draw into a new layer of unhardened photopolymer to form the new cross section. SLA can reach layer thicknesses of under 30 microns. Like DLP, objects printed using SLA have less visible layers other techniques, such as FDM (THRE3D, 2014e).

A.6 Powder Bed Fusion

Powder Bed Fusion can be divided into five categories, namely **Selective Laser Sintering (SLS)** (Figure A-6), Direct Metal Laser Sintering, Electron Beam Melting, Selective Heat Sintering, and Selective Laser Melting. SLS uses lasers to **sinter powdered material**, binding it together to create a solid layer. Then an automated roller deposits a new layer of material to be sintered. SLS is both a cost and time efficient technology, making it ideal for prototyping and end use manufacturing (THRE3D, 2014f).

A.7 Directed Energy Deposition

Directed Energy Deposition can be divided into three categories, namely Electron Beam Direct Manufacturing, Ion Fusion Formation, and **Laser Powder Forming (LPF)** (Figure A-7). LPF can be used to add volume to existing metal objects as well as producing new ones. With LPF, a **laser melts the surface** of the target area while a stream of metal powder is delivered to create a melt pool. The melt pool is directed to deposit a strip of material, building the object layer. The atmosphere is tightly controlled, to allow high-quality, and fully-dense builds. The laser application head is hold by a multi axis joint and the object is built upon a rotary build platform, to allow deposition flexibility for complex geometries. LPF systems are marketed under names such as Direct Metal Deposition, Laser-Engineered Net Shaping, and Laser consolidation. Compared to Powder Bed Fusion Processes, objects created with LPF can be substantially larger, up to several feet long (THRE3D, 2014g).

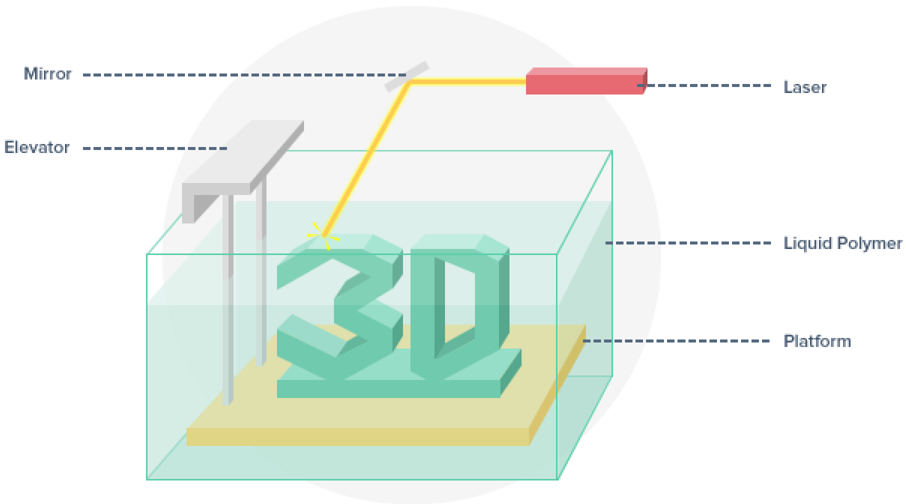


Figure A-5 Stereolithography (THRE3D, 2014e)

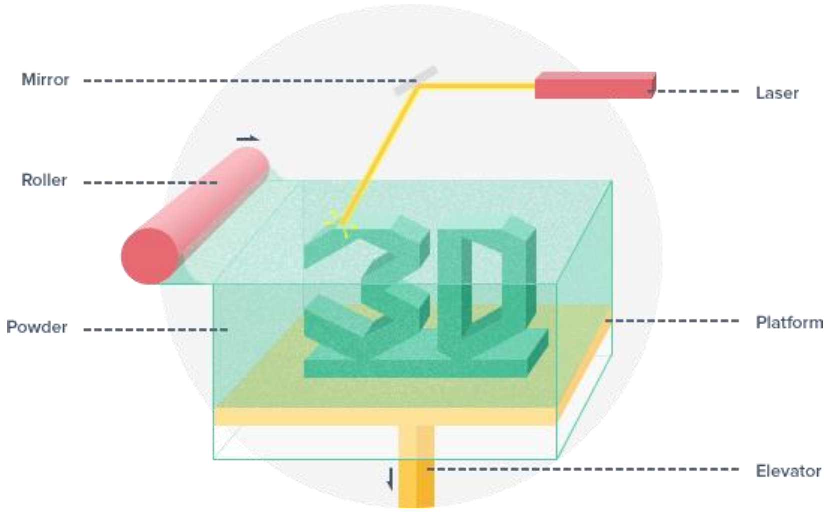


Figure A-6 Selective Laser Sintering (THRE3D, 2014f)

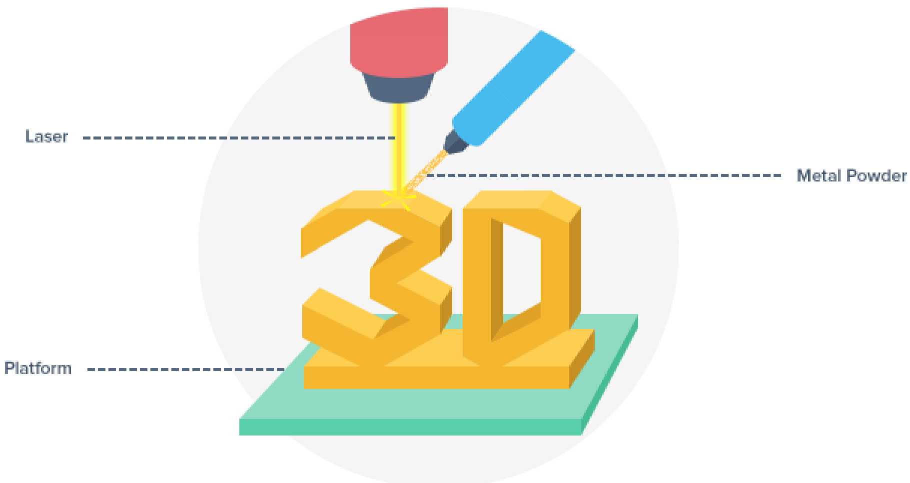


Figure A-7 Laser Powder Forming (THRE3D, 2014g)

Appendix B - Contributing industries for 3DP sector

B.1 Consumer products/electronics

The electronics industry (valued at $3,2 trillion in 2012 (BCC Research, 2007)) is characterized by rapid technical advances and short product lifespans. It requires a flexible technology such as 3DP that can shorten development process and build time. The production of manufacturing and tools equipment especially benefits from 3DP, because of its ability to **incorporate electric circuits** into work pieces which would eliminate process steps. Success factors for increasing market penetration are surface quality, process reliability, part reproducibility, and new materials (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). There is a trend towards increased demand for shorter development time, embedded electronics, and smart microsystems, which could stimulate 3DP deployment. The consumer products industry covers many sub sectors, from cigarettes, to appliances, to clothing. The sectors that are known for experimenting with 3DP or might benefit from 3DP are textiles (valued at $700 billion), furniture ($376 billion), jewellery ($275 billion), sport ($130 billion), toys and collectibles ($75 billion) and specialty food industry ($13 billion) (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). It is however unclear how much each sector is contributing to the 3DP industry.

B.2 Automotive

3DP benefits the automotive industry (that is worth $2.6 trillion (Gausemeier, Echterhoff, & Wall, 2013)) as it reduces costs, time and tooling in conventional manufacturing processes, and accelerates innovation and product development Ducati used 3DP to build a prototype engine that only took 8 months to design and build instead of the usual 28 months (Fortus 3D production systems, 2009). Like the aerospace industry, there is a need for high performance and low weight components especially in the motorsport sector. Luxury and antique cars manufacturers apply 3DP to directly produce small, complex and non-safety relevant parts. Important success factors to increase market share are bigger build chamber volume, increasing process reliability and part reproducibility, and the development of common design rules and certification processes (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). There could be more utilization of 3DP in the future, due to more demand for lightweight parts, replacement parts for antique cars, and personal customization (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011).

B.3 Medical

Implants and prosthetics require a high level of customization since every patient is different. 3DP benefits these sub industries as it offers the flexibility to produce unique products tailored to each patient faster and more economically. A dental technician can produce 20 dental frames per day compared to 450 using a 3D printer. Examples of 3DP applications are prosthetic teeth, arms, legs, and contact lenses (Grenda, 2007). Success factors that will increase the market share are surface quality, process repeatability and reproducibility, and new material (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). Several trends in the industry that might positively influence the 3DP market are increased focus on development of printed organs, tailored surgery strategy using 3DP, and development of aids to improve patient comfort.

B.4 Aerospace

Within the aerospace industry, 3DP is being used for a great variety of applications, especially the design and manufacturing of lighter-weight parts (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011).

The Boeing 787 Dreamliner for example has at least 30 3DP produced parts (Katel, 2012) and a Mars rover about 70 parts (Gausemeier, Echterhoff, & Wall, 2013). 3DP is particularly suitable for the aerospace industry as it deals with geometrically complex products and small batch sizes with high unit costs. The aerospace industry is responsible for 12,1% of the global 3DP revenues (AM Platform, 2014; Best News, 2013) and this is expected to continue with its growth (Gausemeier, Echterhoff, & Wall, 2013). The aerospace industry has a value of about $677 billion (Gausemeier, Echterhoff, & Wall, 2013). A few critical success factors for the aerospace industry to increase market share are definition of common design rules, the establishment of certification processes for 3DP-parts and 3DP-processes (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). There is a trend towards increasing usage of lightweight parts, diversification of product portfolio, and individualization of design (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011), which all will excite 3DP deployment.

B.5 Industrial/business machines

The development and manufacturing of tooling is an expensive and time consuming procedure within a manufacturing process due to complex geometries and high quality of final parts in terms of surface finish, accuracy and reliability (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). 3DP contributes to this industry as it can save time on the production of tooling or it can function as a tooling substitute. The world machine tool industry is worth about $77 billion (The Freedonia Group, 2011). The industry made up 10,8% of the 3DP market (Best News, 2013). 3DP is already widely spread within the tooling industry and it is believed it is going to replace many conventional manufacturing technologies (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). In the future, the industry will experience shorter life cycles of tools, demand for accelerated product development and deployment of universal tool holders (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011).

B.6 Government/military

3DP suits the arms industry as it is more performance driven than cost driven. Also most weapons have a complex structure that are produced in limited quantities of a few thousands parts, and require regular part upgrades (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). 3DP applications can be found in customized gun grips, camera mounts on tanks, and complex military airframe structures. The global arms industry is estimated to be worth at least $410 billion (SIPRI, 2013). It contributes 6,0% to the global 3DP market (AM Platform, 2014). Higher market penetration can be realized through better materials, part quality, and process reliability. Developments that might stimulate 3DP usage within the industry in the future are higher demand for lighter products, higher variety of unmanned aerial vehicles, and on location production or tooling (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011).

B.7 Textiles

The market penetration of 3DP into the textile industry is still mostly limited to experimental purposes. The total market size of the industry is estimated to be around $700 billion in 2012 (Textile Centre of Excellence, 2013). 3DP have been applied in products such as handbags, wristwatch bands, shoes and gloves. Most requirements are already met by conventional manufacturing methods. Only niche markets like the high performance and “intelligent” textiles would benefit from 3DP. Trends in the industry are growing demand for high performance textiles, seamless garment, interest in coating with nano-technology (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011).

B.8 Furniture

3DP is appealing to the furniture industry as it provides designers with more geometric freedom. In addition, through 3DP, production on demand will decrease stock size and production times can be shortened (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). 3DP has been used to make products such as tables, chairs, and lightings. In 2009, 3DP contributed less than one percent to the total furniture industry which was worth $376 billion, since it is still mainly being used for the high price segment (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). In the future it is expected that the demand for individual interior design will increase which can be met by customized designs through 3DP.

B.9 Jewellery

3DP applications are seen in both the high as well as the low price segment of the jewellery industry. It contributes to the industry as the products often have complex geometries. The jewellery industry is worth about $275 billion (Young, 2012). It is unknown how much of this value is contributing to the 3DP market. Although high value materials can be processed, the material choice is still limited. Another success factor to increase market penetration is surface quality. In the future there will be a growing demand for innovative and individual designs, which would demand more 3DP utilization (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011).

B.10 Sport

3DP is deployed in the sport industry to enhance equipment performance, comfort and enjoyment for the athletes as it provides the ability to customize the products tailored to each individual's needs. Examples of 3DP applications in the sport industry are personalized soccer shoes, helmets, and shin pads. The market volume of the sport industry is about $130 billion (PwCIL, 2011). Interest in high quality equipment is rising, however this segment is only a small portion of the total market. Today, 3DP is mainly used for prototyping to test fitting and forms (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). A several notable trends in the industry are shorter lifecycles of products and timely delivery is becoming more important (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011).

B.11 Toys and collectibles

The toys and collectibles industry is characterized by its high level of individual demand (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). 3DP makes it possible for children, who are the main target group, to create their own toys. Older toys might become collectibles for the adults. However the use of 3DP in this industry is still limited, due to the high price of a 3D printer. The industry was worth about $75 billion in 2009. It is believed the industry will increasingly adopt 3DP in the future due to decreasing prices of the 3D printers, increasing demand for lower priced toys and shorter times of delivery (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011).

B.12 Specialty food

In the food industry there is an increasing demand for personalized food, which has led to fashioning of food where the aesthetic appeal of food is desired. With 3DP, food with complex geometric structures can be produced faster and more easily. The specialty food industry is valued at $13 billion in 2009 (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). The contribution of 3DP within this industry is still negligible. 3DP has been used to produce exclusive cakes, sweets, and sushi. Most of the application remain for experimental purposes. 3DP is expected to gain importance in this industry as personalization of food will increase, and there will be more demand for international flavours (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011).

Appendix C - Trade-offs in manufacturing and supply chain strategies

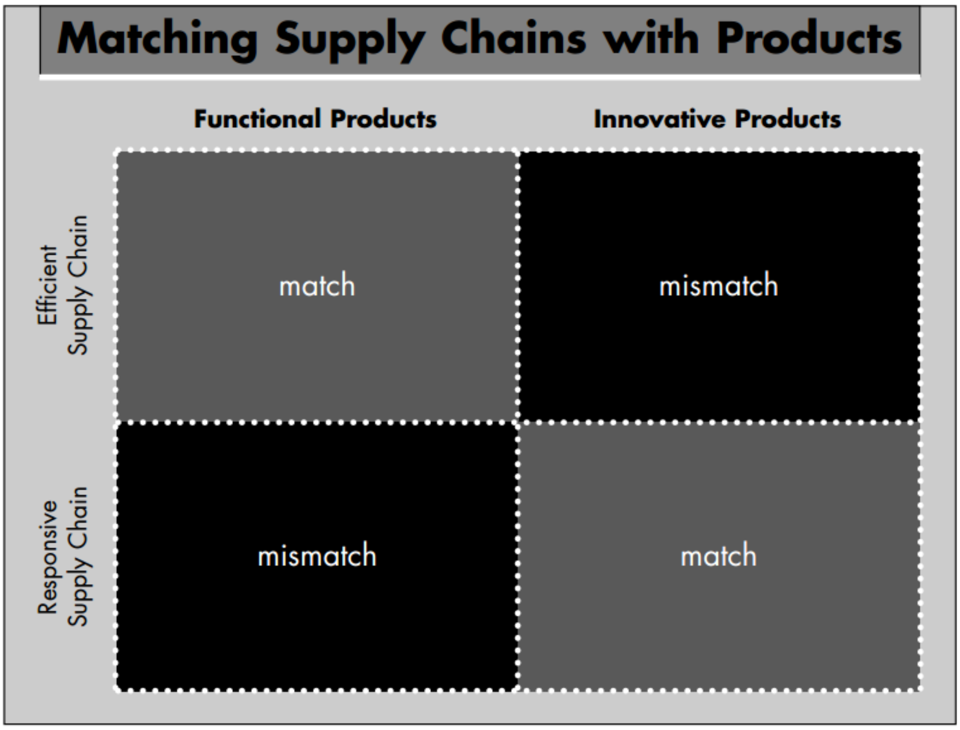


Figure C-1 "Matching Supply Chain with Products" matrix (Fisher, 1997)

Table C-1 Comparison of lean and agile supply chains, adapted from Mason-Jones, Naylor, & Towill (2000)

Distinguishing attributes	Lean supply chain	Agile supply chain
Typical products	Functional (commodities)	Innovative (fashion goods)
Market place demand	Predictable	Unpredictable
Product variety	Low	High
Product life cycle	Long	Short
Variety	Low	High
Customer drivers	Cost	Availability
Profit margin	Low	High
Dominant costs	Physical costs	Marketability costs
Stock penalties	Long term contractual	Immediate and volatile
Purchasing policy	Buy goods	Assign capacity
Information enrichment	Highly desirable	Obligatory
Forecasting mechanism	Algorithmic	Consultative

Table C-2 Assignment of international production strategies to supply chain strategies, adapted from Hofmann, Beck, & Füger (2013)

	Degree of centralization		
Internationalization	High	Medium	Low
	Global	Transnational	Multi-domestic
Description	Centralized production and	Combination of centralized, decentralized and	Decentralized production situated in

	shipments to the market	excentralized production into a global network	the restrictive host markets
Main objectives	Cost-efficiencies (cost leadership strategy)	Cost-efficiency and responsiveness (hybrid strategy, e.g. mass customization)	Responsiveness to customer demands (differentiation strategy)
Corresponding supply chain	Lean	Leagile	Agile

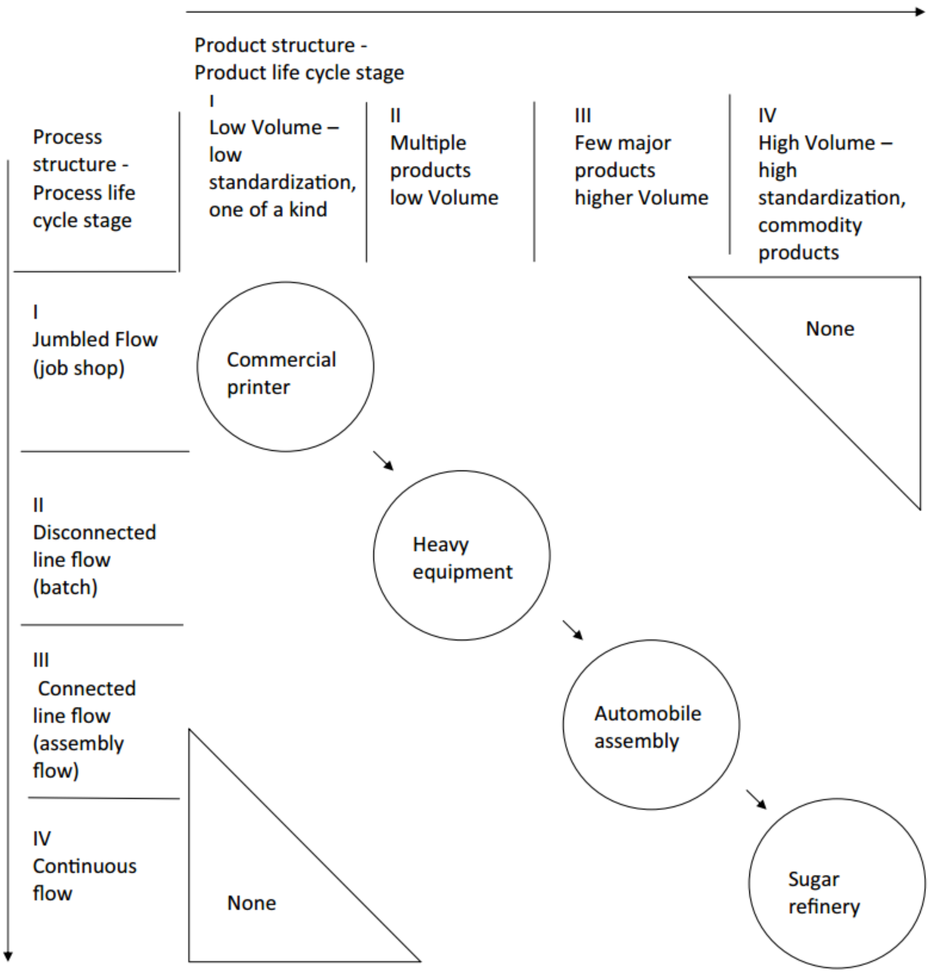


Figure C-2 Product process matrix (Hayes & Wheelwright, 1979)

Supply chain strategy	Lean	Leagile	Agile
Corresponding manufacturing strategy	Make-to-stock	Assemble-to-order	Make-to-order, Engineer-to-order
Production rate	High volume	Medium volume	Low volume
Production process	Continuous production	Batch production, job shop production	One of a kind, project

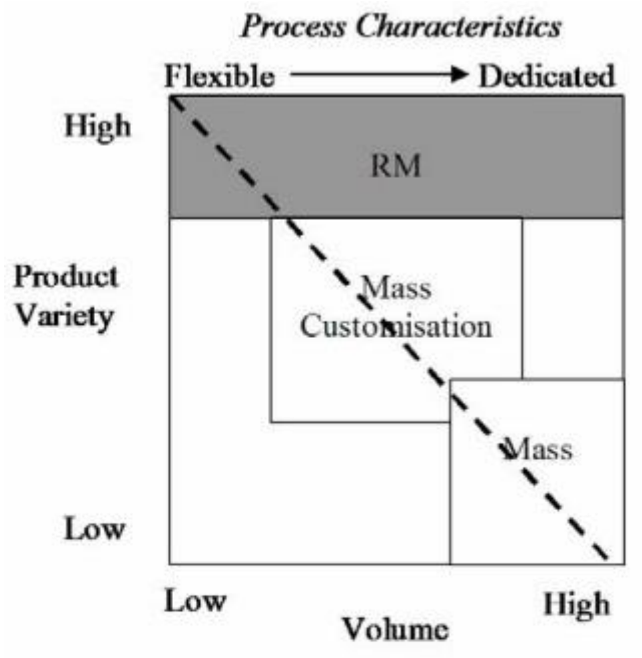


Figure C-3 Manufacturing supply characteristics including RM (Tuck, Ong, Wagner, & Hague, 2009)

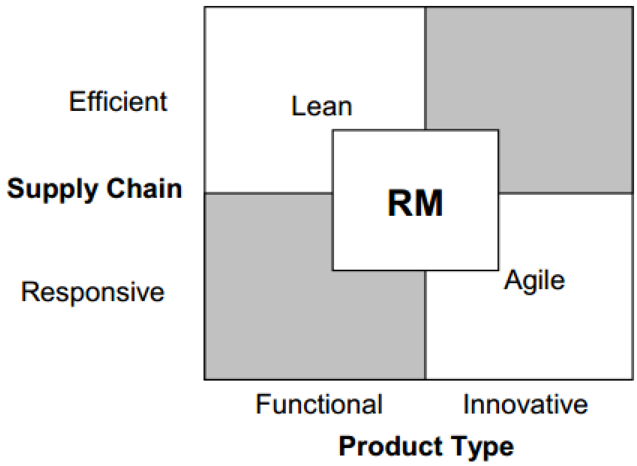


Figure C-4 Modified production and supply chain matrix (Tuck, Hague, & Burns, 2007)

Appendix D - Lean, agile and leagile supply chains

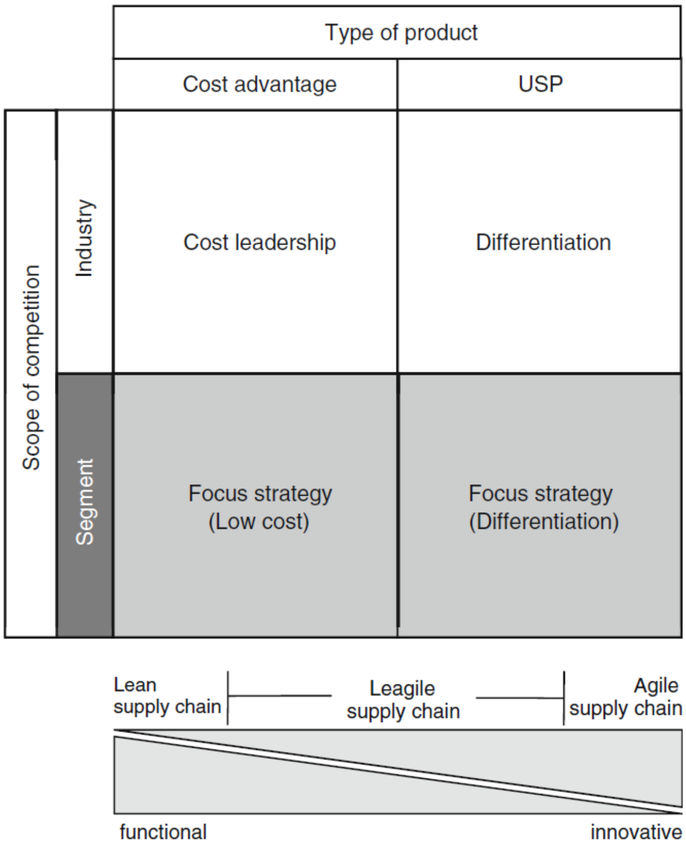


Figure D-1 Link between supply chain strategy with the generic strategy matrix (Hofmann, Beck, & Füger, 2013)

Appendix E - Competitive capability through 3D printing

This section elaborates how 3DP impacts each of the competitive dimensions of the competitive capabilities Quality, Cost, Time, and Flexibility.

E.1 Dimensions of competitive priority Quality

Product quality can be analysed under two different perspectives, namely objective quality and perceived (or subjective) quality (Brunsø, Bredah, Grunert, & Scholderer, 2005). Objective quality can be defined as the technical, measurable and verifiable nature of products/services, processes and quality controls, while perceived quality refers to the consumers' subjective judgments or perceptions of quality.

Perceived quality is determined by intrinsic attributes (e.g. colour, flavour, form) and extrinsic attributes (e.g. brand name, price, origin) (Espejel, Fandos, & Flavián, 2007). Based on intrinsic and extrinsic cues, the consumer forms a certain expectation of the quality (expected quality) at the point of purchase (Acebrón & Dopico, 2000). The difference between the perceived and expected quality will determine the consumer satisfaction (Espejel, Fandos, & Flavián, 2007). For example, if the perceived quality is equal or higher than the expected quality, the consumer will be satisfied, while if it is lower than the expected quality, the consumer will not be satisfied.

What is relevant here, is the **objective quality**, or simply 'quality', since it is independent from extrinsic attributes that are relative and vary widely per product and per consumer. Garvin (1987) proposed eight critical dimensions or categories of quality as a framework for strategic analysis: **performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality** (here mainly referring to a firm's reputation). Whether aesthetics and perceived quality should be included will be discussed in the sub sections, since these appear to be the most subjective dimensions. Firms will choose a combination of these dimensions, depending on their strategy, to increase the quality of their product to gain competitive advantage. In this section, we will discuss the suitability of 3DP to increase these dimensions. It can be argued that if 3DP is suitable to increase a certain dimension, it is more likely to be deployed by a firm.

E.1.1 Performance

Performance refers to a product's primary operating characteristics (Garvin, 1987). The performance of a computer is determined by different aspects, such as data processing speed, response time, or data throughput. The performance of a light bulb is the amount of emitted light per energy unit. However, many products have insignificant performance dimensions, such as a vase or a notepad. How well a vase performs as a water container or how well a notepad holds ink is not interesting. These products usually have a polarized performance dimension, meaning they either fulfil a function or they do not. In contrast with a computer, there are no levels of performance in between. A computer can work at half its full performance, while a vase cannot.

While different products have very different performance dimensions, almost all of them have one common or generic aspect that determines their overall performance: weight. In most cases the lighter version of a product is considered the better performing one, since it quires less energy to be transported. Exceptions are products that require to be "heavy", such as golf clubs, dumbbells, and anchors. With 3DP, the performance-to-weight ratio of products can be improved using an internal lattice or honeycomb structure ("lightweighting") that results in a reduced material use and lighter structures (Scott, et al., 2012; Wohlers, 2012a). Thus it will be assumed whether 3DP is a viable solution to increase the overall performance of a product depends on the importance of its **light weight**. The lighter a product has to be, the more likely 3DP will be considered as a measure to improve this dimension.

E.1.2 Features

Features are all the 'whistles and bells' the product offers that supplement its basic functioning (Garvin, 1987). Different products will have many different features. The most apparent added feature that 3DP can offer a product is the increased ergonomics. Ergonomics concerns the comfort and usability of a product. "Perfect fits" are easier to achieve with the increased design freedom that 3DP offers. Products that require ergonomics usually have a supportive role for the human body, such as shoes, prosthetics, or chairs. It can be assumed, whether 3DP will be a viable tool to increase a product's feature depends on the importance of **ergonomics**. The higher the ergonomics requirement, the more likely 3DP will be deployed.

E.1.3 Reliability

Reliability is the likelihood of a product defect or breakdown within a time period (Garvin, 1987). Products that are built using 3DP are still not up to industry standards in terms of reliability (Wohlers, 2012a), however it is improving (Scott, et al., 2012). Recently it has been reported that 3DP is moving towards "high reliability environments" as a turbine engine manufacturer is preparing to implement 3DP processes into a new engine (IPC, 2013). Also, 3D printed metal guns proved to be as strong and accurate as the conventionally made guns. The downside is "it requires expensive industrial grade equipment" (IEEE Spectrum, 2013). It seems that reliability starting to overcome this barrier and is becoming less of an issue in the near future. It can be said 3DP at its best can match conventionally made variants, but will generally reduce the reliability. Luxury and antique cars manufacturers apply 3DP to directly produce small, complex and non-safety relevant parts. So in general, it can be assumed 3DP is less suitable for products that have a **safety** requirement.

E.1.4 Conformance

Conformance is the degree to which a product conforms to specifications or is produced correctly (Garvin, 1987). Currently 3DP processes are not fully robust. Process consistency between batches and machines is still lacking, there are no in-line process control methods and post processing is often needed to meet product specifications (AM SIG, 2012). In other words 3DP is still lacking in terms of accuracy and finish, which makes reproducibility less optimal. Most accurate machines are capable of holding a tolerance of about 0,125 mm/25 mm (Wohlers, 2010). Thus it can be assumed that if a product requires a low level of **precision**, it is more suitable for 3DP and vice versa.

E.1.5 Durability

Durability can be defined as the amount of usage one gets from a product before it breaks down and repair is not favourable (Garvin, 1987). According to a report by Department for Environment, Food and Rural Affairs (2011) that analysed the public understanding of product life cycle and durability, durability is generally not important, except for products that people chose to "invest" in. This category of products was relative expensive and have a long life cycle. It comprises "investments" made in electronics, large furniture and major appliances. Repairs were considered for these products in contrast with short life cycle products, referred to as "up-to-date" products in the aforementioned report, such as clothes, interior accessories and electronics. 3DP will indirectly increase the durability of a product, since 3DP makes repairs easier while repairs extend the durability of a product. Spare parts can be produced relatively cheap even for out-of-production goods. However, it is unlikely 3DP will increase the durability directly surpassing that of conventionally made products, due to process instabilities. Thus it can be assumed products that have a short **life cycle** are more suitable for 3DP.

E.1.6 Serviceability

Serviceability concerns the speed, courtesy, competence, and ease of repair (Garvin, 1987). When a product breaks down, a quick and responsive repair is desired. 3D printers offers an on demand solution to the volatile spare parts market. Instead of keeping inventory for a wide variety of spare parts, a company can just have a 3D printer that can produce all those parts. The U.S. military for example is already doing this in the field (Burrus, 2013). This will greatly reduce inventory costs and increase efficiency. Repair is only desired for investment products that have a long life cycle (Department for Environment, Food and Rural Affairs, 2011). It can be assumed 3DP will benefits products that require **service and maintenance**.

E.1.7 Aesthetics

Aesthetics concerns how a product looks, feels, sounds, tastes, or smells and it is clearly dependent on an individual's personal judgement and preference (Garvin, 1987). Although this dimension looks like a subjective matter, there appears to be a pattern in consumers' ranking of products on the basis of taste (Garvin, 1987). Also, a recent survey among 931 philosophers shows that 41% accept aesthetic value to be objective, 34,5% subjective, and 24,5% other (PhilPapers, 2009). Here it will be treated as an objective quality dimension. Many philosophic theories exist that try to define and evaluate 'aesthetics'. Architects and industrial designers use 'aesthetic design values' to evaluate creations, such as artistic expression, structural honesty, minimalism, organic forms, or timelessness. Another widely used principle by artists is the Gestalt theory (Behrens, 2002), which assumes humans have perceptual organizing tendencies that propel us to detect structural relations (e.g. symmetry, good continuity, closure, proximity). And it is this characteristic that when we do find these relations, it will be rewarding and give us an aesthetic experience (Hekkert, 2006). 3DP offers designers and engineers an increased design freedom as aesthetic design choices will barely come at a cost, thus it can be assumed it will offer most products an increased aesthetic performance. Conversely, 3DP will less suitable for products with no **aesthetic requirement**, such as a wrench.

E.1.8 Perceived quality

Perceived quality is mostly determined by a company's reputation (Garvin, 1987). Consumers usually do not have complete information about a product, for example durability can rarely be observed directly. Extrinsic cues, such as branding, marketing, and past experience, influence the perceived quality (Garvin, 1987; Mitra & Golder, 2006). Companies can use 3DP to demonstrate their innovative prowess since the technique is still considered relatively new. However most literature today point out 3DP still offers lack of reliability and consistency in quality (LEF, 2012; AM SIG, 2012). This might change in the near future as the technology matures. In short, perceived quality is a highly subjective dimensions and is dependent on the company marketing strategy and the perceptions or expectation of individuals, thus it will not be considered in this research.

E.2 Dimensions of competitive priority Cost

The competitive priority 'cost' here, is assumed to concern costs that are related to the production and can be divided into many dimensions. Different cost estimation techniques for injection moulding have been proposed, such as by Bryce or the Rosato family (Gupta S. , 2005). According to the Rosato family, which is possibly the most respected authority in the injection moulding field (Gupta S. , 2005), cost can be divided into two categories, namely **variable costs** and **fixed costs**. Variable cost (cost that is dependent on the production quantity) is further split into material cost, direct labour cost and energy cost, while fixed cost (cost that is independent of the production quantity) is split into main machine cost, auxiliary equipment cost, tools cost, building cost, overhead labour cost, maintenance cost, and the cost of capital (Rosato, Rosato, & Rosato, 2000).

To use all of these cost dimensions for analysis appears to be complicated, as 3DP costs vary widely between different processes. Several cost models exist for laser sintering, which is currently one of the most used techniques for high volume direct part production (Hopkinson & Dickens, 2003; Ruffo, Tuck, & Hague, 2006). The cost model, RM2005, by Ruffo, Tuck and Hague (2006) can be considered the most accurate as it includes several variables (e.g. machine recycling and production overhead costs) that were not considered in Hopkinson's and Dickens' (2003) model. In the RM2005 cost model, material cost accounts for about 33% of the total cost per part, 38% is incurred by the machine purchase cost, production overhead accounts for 15% (costs incurred due to production, energy, and floor space), labour cost 13%, and administration overhead 1%. This cost division is for the production of 16.000 plastic levers about 35 x 30 x 10 mm in size. However, no cost division is provided for the same production using injection moulding, only the total cost per part. And no cost division examples are provided by the Rosato family (Rosato, Rosato, & Rosato, 2000). This makes comparison of the cost dimensions between injection moulding and 3DP impossible.

Ruffo, Tuck and Hague (2006) do show the total cost comparison between laser sintering and injection moulding (Figure E-1). According to the graph, RM2005 that represents the most accurate 3DP cost estimate, is more cost effective up until about 8500 parts. This is a more conservative estimation (extra cost elements) than the one made by Hopkinson and Dickens (2003), which shows a breakeven point at 14.000 parts. While exact costs are hard to determine for every product, but it can be reasoned whether certain products can be printed in a cost efficient way. According to various literature, this depends on various factors, namely **production volume**, **part size**, **complexity**, and **material**. These will be elaborated further in the following sub sections.

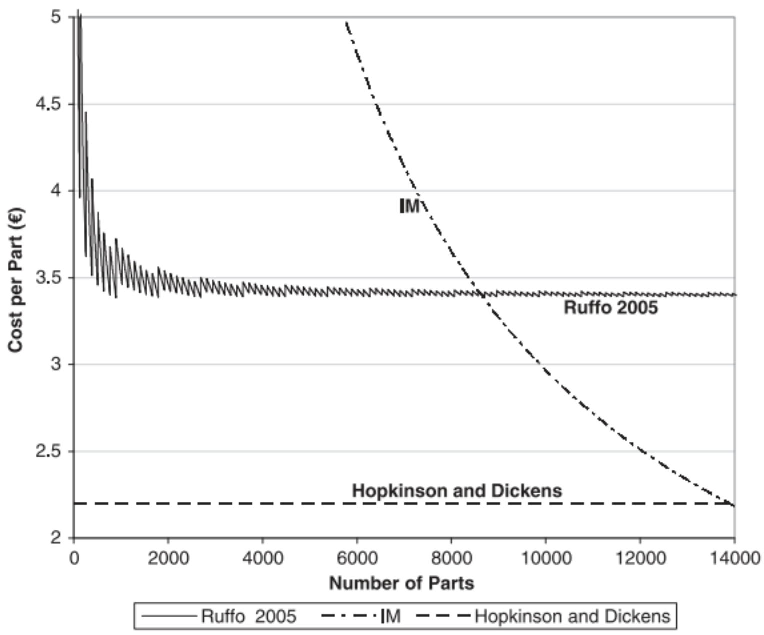


Figure E-1 Cost model comparison laser sintering versus injection moulding (Ruffo & Hague, 2007)

E.2.1 Production volume

While it is unclear which cost dimension is outperformed by which manufacturing technique, it might be more relevant to look at the total production cost. The fact that 3DP appears to be more economical for low to medium production and more expensive for high volume production, could be explained by its smaller fixed cost and higher variable cost. By using 3DP, a manufacturer probably requires less space, tooling equipment, maintenance, and less capital for the main machine. But he will probably have higher variable costs due to the slower build speed and high material cost, which is still at least ten times more expensive for 3DP processes. This results in a lower cost per part at low production volumes, also seen in the graph (Figure E-1), which will be beat by a production setup with high fixed costs and low variable costs in the long run. The faster build speed and the lower material cost of injection moulding processes keep the variable costs low, but requires a higher initial investment cost. The breakeven point should shift towards higher production volumes in the future as material cost and build time, or variable cost, for 3DP decreases. Thus, the **lower the production volume**, the more viable 3DP is as a solution, and vice versa. According to different sources, small production runs of a thousand units down to one per year are considered well suited (LEF, 2012; EOS, 2013b). Thus it will be assumed production below 1.000 units per year is considered low volume production. Above 1.000 units will be considered high volume production.

E.2.2 Part size

Similarly, the part size is a factor that greatly influences the cost. The maximum build envelope varies per printer. Stratasys' largest printer can handle sizes of up to about half a cubic meter (Stratasys, 2013). Giant printers of 12 meters long that can print titanium wing spares and fuselage frames have also been reported (The Economist, 2013). Today, most 3D printers compete in the size range of 85 dm^3 (about 440 x 440 x 440 mm) (Shipp, et al., 2012). The larger the part size, the longer it will take to print the part. Since the 3DP build speed is considerably slower than conventional methods, the part size determines the build time. The longer it takes to a part, the higher the production cost will be per part, thus the breakeven point with injection moulding is reached at less units. For a part that is about 10 cm^3 (35 x 30 x 10 mm), the breakeven point is about 8500 units using laser sintering (Ruffo, Tuck, & Hague, 2006), while for a larger part that is 4000 cm^3 (140 x 190 x 155 mm), the breakeven point is at 180 units (Wohlers, 2010). The numbers will improve over time in favour of 3DP in the future. Thus the **smaller the part size**, the more suitable it is for high volume production with 3DP. Based on the RM2005 model and other literature, it will be assumed products smaller than 1000 cm^3 can be produced at high volume and are thus highly suitable for 3DP, products above 1000 cm^3 can only be produced at low volume.

E.2.3 Complexity

Another factor that will highly influence the production cost is the complexity of the product. The more complex the geometric shape of a part, the more complex the mould has to become or the more tooling is required, which will add respectively to the main machine cost or labour cost. Either way, more parts have to be produced with injection moulding in order for it to breakeven with the 3D printed parts. Since 3DP is almost a toolless process, increased geometric complexity does not result in significantly more work or cost, hence this advantage is often quoted as "complexity for free" (Figure E-2). Thus the **more complex** a part, the more favourable 3DP is as a solution, and vice versa. Geometric complexity can be generally determined by the amount of irregularities and the amount of curves in a design, for example organic shapes are harder to manufacture than orthogonal shapes.

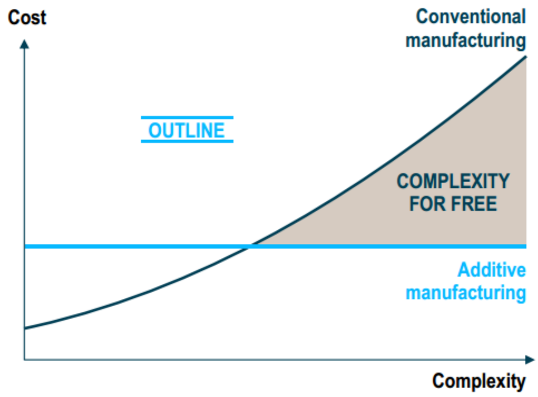


Figure E-2 Complexity and manufacturing cost (Roland Berger Strategy Consultants, 2013)

E.2.4 Material

In terms of material, conventional manufacturing methods have a clear advantage over 3DP in terms of variety, colour, as well as cost. The latter holds true even considering injection moulding processes produce high amounts of resin that account for 43-79% of the production cost (Rosato, Rosato, & Rosato, 2000), and also 50% of the resin produced by 3DP can be recycled (Ruffo, Tuck, & Hague, 2006). The cost advantage is even higher as the volume increases due to economy of scale. Only at low to medium volumes, 3DP can be cost effective.

The price per kilogram of material for 3DP are exceedingly higher than those for conventional manufacturing processes. Today, a kilo of 3DP plastics costs between \$19-\$175 (3ders.org, 2013c), while injection moulding plastics cost between \$2,40-\$3,30 per kilo (Wohlers, 2013b). The relative cheap material cost for injection moulding material is simply due to economy of scale. The most popular 3DP plastics are selling in the range of thousands of kilograms per year, while injection moulding plastics are sold in the millions of kilograms annually (Wohlers, 2010). As demand and volumes increase, the 3DP materials should decline. In the RM2005 cost model, the cost per kilogram plastic is at \$75 (Ruffo, Tuck, & Hague, 2006).

It is less clear how much 3DP metal and ceramic material cost. On Shapeways, the cost per cm^3 printable stainless steel is 5,7 times more expensive than the cheapest plastic and 2,7 times more expensive than the most expensive plastic (Shapeways, 2013). Bronze is respectively 11,4 and 5,4 times more expensive than plastics. Ceramics is only offered as surface finish with a price per cm^2 instead of cm^3 (Shapeways, 2013). The lower availability of 3DP metals and ceramics probably has to do with the technology maturity of the different 3DP processes with each material. It can be assumed that the higher the Manufacturing Readiness Level (MRL), the lower the cost, since a higher MRL indicates that a process is more ready towards full production and is thus more available and cheaper. This is roughly supported by the relatively cheap plastics compared to metals, the unavailability of ceramic materials for 3D production (only 2D) on Shapeways, the lack of data about the cost of 3DP metals and ceramics, and the fact that are 30.000 plastic 3DP machines in operation compared to the

500 metal 3DP machines (European Commission, 2014). Thus, it will be assumed if 3DP is considered, plastic part production will be more cost effective than **other material parts**.

E.3 Dimensions of competitive priority Time

The dimension time, in many literature also referred to as 'delivery' (Ward, McCreey, Ritzman, & Sharma, 1998; Boyer & Lewis, 2002; Krause, Pagell, & Curkovic, 2001). It involves the following dimensions: on-time delivery, delivery speed, and development speed (Laugen & Boer, 2011; Krajewski, Ritzman, & Malhotra, 2010).

E.3.1 On-time delivery

On-time delivery performance (or delivery reliability) is the ability to meet delivery time promises (Krajewski, Ritzman, & Malhotra, 2010). To sustain on-time delivery, a firm's planning needs to take into account demand changes. With a make-to-stock (MTS) setup, a firm requires higher inventory level in order to increase its delivery reliability. A firm with a make-to-order (MTO) setup, requires extra capacity buffer for higher delivery reliability (Shah, 2009). So the performance of this dimension depends on the supply chain setup, the trade-off between extra inventory/capacity cost and stock-out/out of capacity cost, rather than 3DP.

E.3.2 Delivery speed

Delivery speed concerns the reduction in lead time from the receipt of a customer order to the delivery of the product (Krajewski, Ritzman, & Malhotra, 2010). Standardized products can be stocked, so they are usually immediately available and customers have become accustomed to zero waiting time. For customized products, which cannot be stocked, customers expect a waiting time, but it is only acceptable to a certain extend (Coletti & Aichner, 2011). Thus delivery speed is a more important matter for customized products than for standard products. 3DP speeds up customization, as it allows easy reconfiguration of the production process. Thus it will be assumed 3DP will increase the delivery speed of products that require **customization**.

E.3.3 Development speed

The development speed is the rate of introducing a new products (Krajewski, Ritzman, & Malhotra, 2010). Cash savings are the greatest if time to market is minimized (Gebhardt, 2003). 3DP evolved from rapid prototyping of which the goal was to shorten the development phase. This means 3DP can help a firm to achieve a higher rate of product introduction. A high rate of product introduction relates to high product innovation (Greenhalgh & Rogers, 2010). Thus, 3DP will mainly benefit products in **innovative** sectors.

E.4 Dimensions of competitive priority Flexibility

Companies require flexibility in their operations to deal with uncertainties. Flexibility can be divided into the following dimensions: Customization, variety, and volume (Krajewski, Ritzman, & Malhotra, 2010).

E.4.1 Customization

Through customization, a firm can satisfy the unique needs of each customer by adapting product designs (Krajewski, Ritzman, & Malhotra, 2010). Due to the toolless nature of 3DP, it is believed to be the enabler of (mass) customization (Tuck & Hague, 2006; Reeves, Tuck, & Hague, 2011). The production process is highly flexible and easily reconfigured to produce modified variants. It removes restrictions throughout the product development and production process, and enables cost-effective low volume production. Hence, 3DP would be especially suitable for products that require **customization**.

E.4.2 Variety

Variety concerns the handling of a wide assortment of products (Krajewski, Ritzman, & Malhotra, 2010). The products are not necessarily unique to customers and the demand may be repetitive. Product variety require higher volume processing capacity than with customization (Krajewski, Ritzman, & Malhotra, 2010). Higher variety results in a larger inventory and higher complexity in the supply chain, resulting in higher costs (Shah, 2009). To create variety with limited complexity, firms are incorporating the so called "leagile" strategy, in which modular components are mass produced until the point where it allows to be customized (postponement). 3DP eliminates the need for tooling and this makes the production process highly flexible. 3DP should be able to aid manufacturers in the customization stage. Thus it can be assumed 3DP can beneficial for products that require **variety**.

E.4.3 Volume flexibility

Flexibility in volume is the ability to adjust processes to handle demand fluctuations (Krajewski, Ritzman, & Malhotra, 2010). In a market with uncertain demand, manufacturers have to be able to handle excess capacity and inventory, or adjust capacity without accumulating excess capacity and inventory (Krajewski, Ritzman, & Malhotra, 2010). 3DP is suitable for producing small batches and not for large quantities. Products with a predictable demand are more likely to adopt a manufacturing and supply chain setup that maximizes cost efficiency, instead of flexibility (Hofmann, Beck, & Füger, 2013). Thus products with **uncertain demand** are more suitable for 3DP.

Appendix F - Determination of fuzzy product characteristics

In most literature, it is unclear what is meant with certain product characteristics that are well suited for 3DP, such as “small products” or “complex geometries”. These are relative (fuzzy) terms and are open for interpretation. In this section, the goal is to clarify and define these terms (Table Q-7). While not every definition can be supported by quality reference, an effort is made to do so as much as possible. The rest will be based on best judgement.

Table F-1 Definitions of the product characteristics

Product characteristic	Value and description	Value and description
Light weight	**Not important**	**Important**
	A lighter version of the product will not result in any significant benefits for the user nor the producer.	A lighter weight is an important requirement and will result in benefits for the user and/or the producer.
Ergonomics	**Not important**	**Important**
	The product is usually not subject to any physical contact from the user.	The product is subject to regular physical contact, or fulfils a supportive role for a (human) body.
Safety	**Not important**	**Important**
	Products of which failure is unlikely to cause significant negative consequences.	Products of which failure might have significant negative consequences either financially or physically.
Precision	**High**	**Low**
	Products with a low error tolerance level, e.g. products associated with microtechnology, sensitive instruments.	Products a high error tolerance level.
Life cycle	**Short**	**Long**
	Products of which the risk for obsolescence is less than 1 year (Fisher, 1997). Here it will be assumed anything below 2 years, to limit the values to two options.	Products of which the risk for obsolescence is longer than 2 years (Fisher, 1997).
Service/ maintenance	**Not important**	**Important**
	Products that do not require regular service and maintenance.	Products that regular service and maintenance.
Aesthetics	**Not important**	**Important**
	Products with no decorative function.	Products with a decorative function.
Volume	**High**	**Low**
	More than 1.000 units per year (Section E.2).	Less than 1.000 units per year (Section E.2).
Part size	**Large**	**Small**
	Above 1.000 cm^3 (Section E.2).	Below 1.000 cm^3 (Section E.2).

Complexity	**Low**	**High**
	The product's geometric shape is contains mostly plane sections (Kerbrat, Mognol, & Hascoët, 2011), contains few components.	The product's geometric shape contains many changes in surface orientations (Kerbrat, Mognol, & Hascoët, 2011), and consists of many components.
Material	**Other material**	**Plastic**
	Products that primarily contain materials other than plastics.	Products that primarily contain plastics.
Customization	**Not important**	**Important**
	Products that do not require personalization.	Products that require personalization.
Variety	**Low product variety**	**High product variety**
	Products that are standardized with limited variants.	Products that have numerous variations per category (Fisher, 1997).
Demand uncertainty	**Low**	**High**
	Products of which the demand is predictable, which usually is the case with "functional products" (satisfying basic needs) (Fisher, 1997). Also standardized products have lower demand volatility (Egri & Váncza, 2007).	Products of which the demand is highly unpredictable, which usually is the case with "innovative products" (fashionable) (Fisher, 1997). Also customized products have volatile demand (Egri & Váncza, 2007).

Appendix G - Weights of competitive capabilities

The weights of different competitive capabilities based on their importance perceived by the industry have been shown in various studies. In this paper, the data of the most recent study will be considered with the largest sample size and geographical coverage, which is “The International Manufacturing Strategy Survey” by Laugen and Boer (2011).

The International Manufacturing Strategy Survey (IMSS) is a research carried out periodically since 1992 by a global network of research groups that studies manufacturing strategies, practices and performances within the manufacturing industries through a detailed, globally distributed questionnaire. The companies in the database represent manufacturers from various industries, such as metal engineering, electronics, automotive and semiconductor sectors. The IMSS V sample consists of data from 677 medium to large manufacturing companies from 19 countries worldwide with employees ranging between 410 and 7200. To illustrate the importance of the competitive capabilities, the companies had to rate them on a Likert scale ranging between 1 (not important) and 5 (very important).

Table G-1 Importance of competitive capabilities in the last three years (1=not important; 5=very important) (Laugen & Boer, 2011)

	Competitive priorities											
	Selling prices	Product design and quality	Conformance quality	Dependable deliveries	Faster deliveries	Customer service	Product range	New products more frequently	More innovative products	Order size flexibility	Environmentally sound products	Committed social responsibility
East Europe	4.1	4.1	4.4	4.2	3.9	3.3	3.2	2.9	3.2	3.5	3.0	2.7
West Europe	3.8	4.2	4.0	3.7	3.4	3.6	2.9	2.7	3.3	2.9	2.9	2.6
North Europe	3.4	4.1	3.8	4.0	3.7	3.9	3.2	3.2	3.5	3.2	2.9	2.5
South Europe	3.8	4.1	4.1	3.9	3.7	4.0	3.2	2.9	3.5	3.0	2.9	2.5
North America	3.8	4.3	4.4	4.2	3.8	3.9	3.1	2.8	3.3	3.0	3.2	3.2
South/Central America	4.3	4.4	4.2	4.2	4.2	4.2	3.8	3.6	4.0	3.9	3.4	3.4
Asia	3.7	4.3	4.3	4.4	4.2	4.3	3.8	3.8	3.8	3.7	3.8	3.7
Total	3.8	4.2	4.2	4.1	3.8	3.8	3.3	3.1	3.5	3.3	3.2	3.0

The competitive capabilities shown in Table G-1 can be considered competitive dimensions, which explains why there are so many compared to the common four competitive capabilities (quality, cost, time, and flexibility) in other studies. These competitive dimensions can be consolidated to from the four general competitive capabilities initially proposed by Hayes and Wheelwright (1984) that stayed much the same after 15 years of empirical research (Krause, Pagell, & Curkovic, 2001). Dimensions that do not fit into any of the general competitive priority, such as “environmentally sound products”, are not included. This idea of consolidating the dimensions to form the main competitive capabilities is borrowed from Cagliano, Caniato, Kalchschmidt, and Golini (2010), who used previous IMSS papers to perform several analyses. The consolidated dimensions with the average values are shown in Table G-2.

Table G-2 Importance of the consolidated competitive capabilities from IMSS

	Totals from IMSS V	Average
Quality		**4,20**
Product design and quality	4,2	
Conformance quality	4,2	
Cost		**3,80**
Selling prices	3,8	
Time		**3,67**
Dependable deliveries	4,1	
Faster deliveries	3,8	
New products more frequently	3,1	
Flexibility		**3,30**
Product range	3,3	
Order size flexibility	3,3	

To verify that the average values are acceptable since the competitive dimensions differ from those from this research, they can be compared to the results in other studies. It can be assumed if the values fall between the results from the other studies, they can be considered acceptable, despite using different competitive dimensions. These results are shown in Table G-3. Studies that have used a Likert scale ranging from 1-7 are normalized to 1-5 scale. The deviation from the IMSS average values are shown in brackets. Compared to the results from other studies, the average values seem acceptable. The values resemble the most (least deviation) with the results from Ward, McCreey, Ritzman and Sharma and deviate the most from Boyer and Lewis. Of the four studies, Boyer and Lewis have relatively the highest values, Kim and Arnold second highest, IMSS V the third, and Ward, McCreey, Ritzman and Sharma have the lowest values.

Table G-3 Importance of competitive priorities in various studies (1-7 Likert scales converted to 1-5 scales) (Laugen & Boer, 2011; Boyer & Lewis, 2002; Ward, McCreey, Ritzman, & Sharma, 1998; Kim & Arnold, 1996)

	IMSS V (Laugen & Boer, 2011)	Boyer & Lewis (2002)	Ward, McCreey, Ritzman, & Sharma (1998)	Kim & Arnold (1996)
Quality	4,20	4,64 (+0,44)	4,00 (-0,20)	4,48 (+0,28)
Cost	3,80	4,01 (+0,21)	3,83 (+0,03)	4,10 (+0,30)
Time	3,67	4,61 (+0,94)	3,65 (-0,02)	4,29 (+0,62)
Flexibility	3,30	4,00 (+0,70)	3,26 (-0,04)	3,79 (+0,49)

For the sake of simplicity, equal weights will be assumed in this research, as the difference between the importances of the four competitive capabilities do not vary enough to cause significant score differences. And since different companies in the same sector can focus on different capabilities, it is best to consider each capability as equals. Thus it is believed that adding the different capability informance factors adds little value to the calculations.

Appendix H - Market analyses: 3DP deployment

In this section, the goal is to assess the markets that are known for 3DP deployment in order to validate that the 3D Competitiveness Score Model can produce scores that represent the 3DP market penetration.

H.1 Medium-high 3DP adoption markets

The medical industry belongs to the top three drivers of the 3DP sector. Implants and prosthetics require a high level of customization since every patient is unique. 3DP benefits these sub industries as it offers the flexibility to produce unique products tailored to each patient faster and more economically. The particularly well suited products for 3DP production are dental crowns, hearing aids, and prosthetics. For these three products it is known that 3DP has made a significant impact in the recent years. We will test dental crowns and hearing aids using the 3DCSM.

H.1.1 Dental industry

In the recent years, the 3DP market has grown explosively within the dental industry, which is the fastest growing field of application for 3DP (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011). According to E-Manufacturing Solutions (EOS, 2013a), the technology and market leader for design-driven and integrated solutions for 3DP, crowns and bridges have been produced using 3DP since 2005 (Figure H-1). A dental technician can produce 20 dental frames per day compared to 450 using a 3D printer. Over the world, there are 60 Direct Metal Laser Sintering (DMLS) systems installed that produce around 6,8 million units every year. This is expected to grow in the future due to the increasing purchasing power for dental aesthetics and the progressively aging population (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011).

Figure H-1 A building platform can be charged with up to 450 crowns (EOS, 2013a)

H.1.2 Hearing aid industry

The hearing aid industry is worth $2 billion and it is predicted to grow at an annual rate of 2.8% between 2013 and 2016 (Sharma, 2013). 3D printing in the hearing aid production today is quite common. More than 90% of today's hearing aid shells are 3D printed (Figure H-2) (Wile, 2013), and according to the head consultant from Econolyst, there are about 10 million 3D printed hearing aids in circulation worldwide (Peels, 2011). Customizations, which are often desired, are no longer an issue using 3DP. It reportedly has shortened the general nine-step fitting process down to three (Sharma, 2013). However the total cost to produce hearing aids have not reduced. While 3DP has reduced labour cost and increased efficiency, it requires on the other hand a high capital for the machinery and software (Sharma, 2013).

Figure H-2 3D printed hearing aid outer shells (Peels, 2011).

H.2 Low-medium 3DP adoption markets

The electronics, consumer goods, and automotive industry are believed to have low to medium 3DP adoption. While these industries are one of the largest drivers of the 3DP sector, due to their large market size, the overall adoption can be considered to be lower than that of medical industries.

H.2.1 **Automotive industry**

The automotive industry that is worth $2.6 trillion (Gausemeier, Echterhoff, & Wall, 2013) is the second largest driver of the 3DP sector. 3DP benefits the automotive industry as it reduces costs, time and tooling in conventional manufacturing processes, and accelerates innovation and product development processes (Gausemeier, Echterhoff, & Wall, 2013). While the industry only offers a few types of products, namely cars, light and heavy commercial vehicles, and heavy busses (OICA, 2014), the variety per type is massive due to customization options (automatic/manual gearbox, gasoline/diesel/gas/electric/hybrid engine, etc.). Of the top ten ranking automobile manufacturers in 2012, cars represented 83% of their unit sales, light and heavy commercial vehicles 16%, and heavy busses 0,1% (OICA, 2014). Thus cars will be chosen to be tested using the 3DCSM.

Figure H-3 3D printed race car, named Areion (Materialise, 2012)

3DP has been used to produce the entire frame of a race car (Figure H-3) (Materialise, 2012), however the method is likely unsuitable for production at large quantities as the printing process takes three weeks (3ders.org, 2012). 3DP is often used for prototyping. Ducati used 3DP to build a prototype engine that only took 8 months to design and build instead of the usual 28 months (Fortus 3D production systems, 2009). Like the aerospace industry, there is a need for high performance and low weight components especially in the motorsport sector. Cars are such complex products, that it is difficult to test using the 3DCSM. A car consists of parts from various other industries, such as electronics, textile products, mechanical parts. And each part probably has different market characteristics, for example the tires are likely mass produced while the interior can be custom made. This results in a supply chain that is one of the most complex among manufactured goods. Thus it is unlikely that a whole car will ever be fully printed. However, in a complex product lies the opportunity to consolidate processes and parts in order to simplify. Most 3DP deployments exist today for the purpose of prototyping and testing, with occasionally a custom made part. Direct part production is used by luxury and antique cars manufacturers for small, complex and non-safety relevant parts.

Figure H-4 Project Ara, the upgradable, modular smartphone (Stone, 2014)

H.2.2 **Electronics industry**

The largest revenue in the consumer electronics industry comes from **smartphones** that generate 35%

of the total sales revenue (Deloitte, 2014). We will test smartphones using the 3DCSM.

Currently 3DP deployment in the smartphone industry is limited to prototyping. Most articles revolve around producing personalized smartphone covers rather than internal parts. 3DP has been used to build smartphone prototypes (Jacques, 2014). Optomec is a 3D printing company specialized in printing electronics that recently have announced they soon will have a new process ready for printing antennas at high volume (Optomec, 2013). And another company named nScript Inc. is currently negotiating deals to sell 3D printed antennas to every smartphone manufacturer in the US (Taylor, Tuning In To Potential: 3D Printed Tiny Antennae, 2014). It is only since Motorola's Project Ara in 2013 (Figure H-4), which strives to build a customizable, modular smartphone, that 3D printing is making more of an inroad into the smartphone industry. Partnering with 3D Systems, Motorola hopes to realize these new type of phones with upgradable hardware (Lee, 2013). The deployment of 3DP to produce smartphone parts as of today, should also be very limited, although it appears this might change in the near future.

H.2.3 Consumer products industry

Jewellery industry is one of the consumer products sector that is known for deploying 3DP both in the high as well as the low price segment of the jewellery industry.

Jewellery products are often small in size, have complex geometries and are high valued. While the market is split in two segments, one in which the emphasis is on highly exclusive quality materials, and the other on cheap and creative products (e.g. costume jewelleries), both market can benefit from 3DP as it offers increased design freedom. Today, the technology is already being deployed for direct part production. The large Dutch retail chain HEMA offers 3D printed golden necklaces as of 2013 (Figure H-5) (3ders.org, 2014), Cookson Precious Metals is a global supplier of fabricated precious metals for the jewellery industry in US, UK, France and Spain and deploys 3DP for a part of their production (Vallance, 2013). As for the low value segment, various retailer offer affordable, customized, 3D printed jewellery, such as Cubify, Shapeways, and Zazzy. It appears 3D printed jewellery is present in the high value segment as well as the low value segment.

Figure H-5 3D printed necklace by HEMA (3ders.org, 2014)

H.3 None-existent to low 3DP adoption markets

While rubber and glass materials can be 3D printed, their market is currently practically non-existent. These market will be tested as a control group using the 3DCSM.

H.3.1 Tyres industry

The European tyres and rubber industry generated a turnover of €46 billion in 2011. The industry exported 67 million tyres (€6,3 billion) and imported 103 million tyres (€6,2 billion) (ETRMA, 2013). The European tyre production is estimated at 21% of the world tyre production. 69% of the global tyre manufacturing revenue is made by top ten tyre producers in the world (ETRMA, 2013). 3D printing natural rubber products is not yet possible. Different companies today are experimenting with rubber-like materials, which are technically different type s of flexible plastic that simulate rubber properties (Figure H-6). Even though it would be possible to 3D print for example high performance rubber-like tyres, it will only be suitable for the high value segment as the majority of tyres are still mass produced, no customization is usually required, tyres can be quite large in size, and have a fairly low replacement cycle. The market penetration of 3D printed tyres is obstructed by many technological limitations. Opportunity for 3D printed rubbery goods lies in other rubber goods, which account for a smaller share of the rubber industry.

Figure H-6 Prototype tyre by Stratasys (Stratasys, 2014a)

H.3.2 Glass industry

Glass is one of those heavily commoditized manufactured products that are mostly mass produced. The glass industry is considered mature and struggles to identify new markets (The Gale Group, 2014). In other words, innovation in this industry is low. The glass industry produces several types of products, such as flat glass (e.g. window glass), glass containers (e.g. bottles), glass tableware, and glass filament fibre, of which the glass container is the largest group (about 50%) in production volume (Ecofys, 2009). We will test glass containers using the 3DCSM.

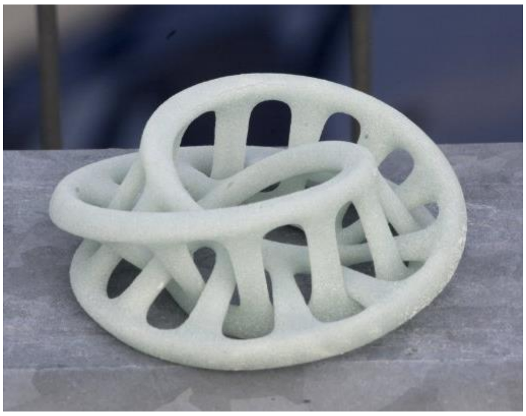


Figure H-7 The 3D printed glass model of 9,5 cm in diameter costs $80 (Shapeways, 2010).

Technically it is possible to 3D print glass products (Figure H-6), however they are not yet see-through (Shapeways, 2010). The US glass container industry is worth about $8,4 billion in 2008 (The Gale Group, 2014). The market penetration of 3D printed in this industry today is practically non-existent, mainly due to the fact 3DP using glass material is relatively new and expensive. Market adoption will likely remain limited in the near future due to market characteristics such as the high commoditization, fairly simple geometries, and low innovation rate.

H.4 3D Competitiveness Score Model results

Deployment of 3DP for direct part production is mostly present in the medical sector. In the automotive, electronics, and consumer goods industry, 3DP is mostly used for prototyping and with limited use of direct part production. The tyres and glass industry are still only prototyping with 3DP. These products will be tested using the 3DCSM. If the 3DCSM can reflect the success of 3DP in a certain industry, it should give high scores for the medical industry and low scores for the tyres and glass industry. The full explanation of the scoring per product are shown in Appendix I. The summarized results are shown in Table Q-7, Table H-2, and Table H-3.

The 3DCSM scores from the table indicate that the 3DCSM seem able to produce scores that reflect the success of 3DP in a particular market. However, given the high scores for most industries, the scores probably do not reflect the current 3DP market penetration. Medical industry products scored the highest (72,9%-87,5%), automotive, electronics, consumer goods industry products scored average (39,6%-54,2%), and tyres and rubber, and glass industry scored the lowest (-8,3%-4,2%). It is important to note that more products should be tested using the 3DCSM for a better validity. Due to the time constraint, the number of products to be tested has been limited to these seven products.

Table H-1 Summarized scores of productis with medium-high 3DP market penetration

Industry	Medical	
Tested product	Crowns	Hearing aids
3DP deployment	Direct part production	Direct part production
Quality score	25%	50%
Cost score	66,7%	100%
Time score	100%	100%
Flexibility score	100%	100%
Total 3DCSM score	**72,9%**	**87,5%**

Table H-2 Summarized scores of products with low-medium 3DP market penetration

Industry	Automotive	Electronics	Consumer
Tested product	Cars	Smartphones	Jewellery
3DP deployment	Prototyping, limited direct part production	Prototyping, limited direct part production	Prototyping, limited direct part production
Quality score	25%	25%	0%
Cost score	-66,7%	0%	66,7%
Time score	100%	100%	50%
Flexibility score	100%	100%	100%
Total 3DCSM score	**39,6%**	**56,3%**	**54,2%**

Table H-3 Summarized scores of with none-existent-low 3DP market penetration

Industry	Tyres and rubber	Glass
Tested product	Tyres	Glass containers
3DP deployment	Prototyping	Prototyping
Quality score	0%	50%
Cost score	-100%	-66,7%
Time score	0%	0%
Flexibility score	66,6%	33,3%
Total 3DCSM score	**-8,3%**	**4,2%**

Appendix I - Scoring products using 3D Competitiveness Score Model

Table I-1 Scoring of dental crowns using the 3D Competitiveness Score Model

Crowns (dental)	Weight	Diminishment ←	→	Improvement	% of max		Explanation
		-1	0	1			
Quality	1						
Performance			Unimportance of light weight	Importance of light weight	0		Weight is not an issue.
Features			Unimportance of ergonomics	Importance of ergonomics	1		Crowns fulfil a supportive role for the human body, thus require to be ergonomic.
Reliability		Importance of safety	Unimportance of safety		0		Crowns do not have a safety requirement
Conformance		High precision	Low precision		-1		Medical products require decent amount of accuracy.
Durability		Long life cycle	Short life cycle		-1		Crowns last between 10-20 years (Horne, 2013).
Serviceability			Unimportance of service/maintenance	Importance of service/maintenance	1		Crowns require to be checked for integrity on a yearly basis.
Aesthetics			Unimportance of aesthetics	Importance of aesthetics	1		Crowns have a decorative function.
				Subtotal	**1**	**25%**	
Cost	1						
Production cost		High volume		Low volume	1		"Most dental labs are small operations… making about 5 to 10 models per day (Thryft, 2013)." Each crown is unique.
		Big part size		Small part size	1		Crowns are smaller than 1.000 cm³.
		Low complexity		High complexity	1		Many irregularities in the surface orientation.
		Other material	Plastics		-1		85% of dental crowns and bridges are metal-based and 15% ceramic-based (Everyday Health, Inc., 2013).
				Subtotal	**2**	**66,7%**	
Time	1						
Delivery lead time			Unimportance of customization	Importance of customization	1		Customization in crowns is a requirement.
Rate of product introduction			Low innovation	High innovation	1		The medical industry is considered an innovative sector.
				Subtotal	**2**	**100%**	
Flexibility	1						
Customization			Unimportance of customization	Importance of customization	1		
Variety			Low variety	High variety	1		Crowns are offered as one-offs.
Volume flexibility			Low demand uncertainty	High demand uncertainty	1		Highly customized products have volatile demand (Egri & Váncza, 2007).
				Subtotal	**3**	**100%**	
				Total		2,917	
				% of max		72,9%	The maximum score is 4

Table I-2 Scoring of hearing aids using the 3D Competitiveness Score Model

Hearing aid	Weight	Diminishment ←	→	Improvement		% of max	Explanation
		-1	0	1			
Quality	1						
Performance			Unimportance of light weight	Importance of light weight	1		Lighter hearing aids are preferred over heavier ones.
Features			Unimportance of ergonomics	Importance of ergonomics	1		Hearing aids fulfil a supportive role for the human body.
Reliability		Importance of safety	Unimportance of safety		0		Hearing aids do not have a safety requirement.
Conformance		High precision	Low precision		-1		Medical products require decent amount of accuracy.
Durability		Long life cycle	Short life cycle		-1		Hearing aids last for about 5-7 years (Emory Healthcare, 2014).
Serviceability			Unimportance of service/maintenance	Importance of service/maintenance	1		Hearing aids usually require servicing and repair.
Aesthetics			Unimportance of aesthetics	Importance of aesthetics	1		Hearing aids have a decorative function.
				Subtotal	**2**	**50%**	
Cost	1						
Production cost		High volume		Low volume	1		While millions are being made per year (Kirkwood, 2013), most hearing aids are customized, thus a low volume of the same hearing aid is produced.
		Big part size		Small part size	1		Hearing aids are smaller than 1.000 cm^3.
		Low complexity		High complexity	1		Many irregularities in the surface orientation.
		Other material	Plastics		0		Hearing aids are mostly made of plastics, with internal electronics made from metal (University of Rochester Medical Center, 2014).
				Subtotal	**3**	**100%**	
Time	1						
Delivery lead time			Unimportance of customization	Importance of customization	1		Customization in hearing aids is often a requirement.
Rate of product introduction			Low innovation	High innovation	1		The medical industry is considered an innovative sector.
				Subtotal	**2**	**100%**	
Flexibility	1						
Customization			Unimportance of customization	Importance of customization	1		
Variety			Low variety	High variety	1		Hearing aids are often offered as one-offs.
Volume flexibility			Low demand uncertainty	High demand uncertainty	1		Highly customized products have volatile demand (Egri & Váncza, 2007).
				Subtotal	**3**	**100%**	
				Total		3,50	
				% of max		**87,5%**	The maximum score is 4

Table I-3 Scoring of cars using the 3D Competitiveness Score Model

Car	Weight	Diminishment ←	0 →	Improvement		% of max	Explanation
		-1	0	1			
Quality	1						
Performance			Unimportance of light weight	Importance of light weight	1		Weight reduction is an important goal.
Features			Unimportance of ergonomics	Importance of ergonomics	1		Cars are subject to regular physical contact.
Reliability		Importance of safety	Unimportance of safety		-1		Cars require to be safe.
Conformance		High precision	Low precision		-1		Cars require high precision manufacturing.
Durability		Long life cycle	Short life cycle		-1		Cars should last for more than 5 years. The average of a car in the U.S. is 10,8 years (Gorzelany, 2013).
Serviceability			Unimportance of service/maintenance	Importance of service/maintenance	1		Cars require regular service and maintenance, repairs are common.
Aesthetics			Unimportance of aesthetics	Importance of aesthetics	1		Cars have an aesthetic function.
				Subtotal	**1**	**25%**	
Cost	1						
Production cost		High volume		Low volume	-1		A large quantity of cars are still build to stock. In Europe, 52% of the cars are sold from stock, this is 40% in Japan (Holweg, 2008), and 85% in the U.S. (Muller, 2010). These cars can be considered mass produced.
		Big part size		Small part size	-1		Cars are large products, way larger than 1.000 cm^3.
		Low complexity		High complexity	1		Many irregularities on the surface, also contains many different components.
		Other material	Plastics		-1		Cars contain primarily metal.
				Subtotal	**-2**	**-66,7 %**	
Time	1						
Delivery lead time			Unimportance of customization	Importance of customization	1		Customization in cars is desired.
Rate of product introduction			Low innovation	High innovation	1		The automotive industry is considered an innovative sector.
				Subtotal	**2**	**100%**	
Flexibility	1						
Customization			Unimportance of customization	Importance of customization	1		
Variety			Low variety	High variety	1		
Volume flexibility			Low demand uncertainty	High demand uncertainty	1		The automotive market varies greatly each year in different geographic areas and for different car models, due to various factors, such as social, political and general economic conditions, introduction of new models and technologies (Toyota Motor Corporation, 2013a).
				Subtotal	**3**	**100%**	
				Total		1,583	
				% of max		**39,6%**	The maximum score is 4

Table I-4 Scoring of smartphones using the 3D Competitiveness Score Model

Tyres	Weight	Diminishment	← →	Improvement	% of max		Explanation
		-1	0	1			
Quality	1						
Performance			Unimportance of light weight	Importance of light weight	0		Weight reduction is not an important issue.
Features			Unimportance of ergonomics	Importance of ergonomics	1		Smartphones are subject to regular physical contact.
Reliability		Importance of safety	Unimportance of safety		0		Smartphones do not have a safety requirement. Not to be confused with health safety requirement.
Conformance		High precision	Low precision		-1		Smartphones require high precision manufacturing (microtechnology).
Durability		Long life cycle	Short life cycle		-1		The replacement cycle of a smartphone is 24 months in 2013 (Deloitte, 2014), and is believed to increased further (Gartner, 2014).
Serviceability			Unimportance of service/maintenance	Importance of service/maintenance	1		Smartphones sometimes require repairs.
Aesthetics			Unimportance of aesthetics	Importance of aesthetics	1		Smartphones have an aesthetic function.
				Subtotal	**1**	**25%**	
Cost	1						
Production cost		High volume		Low volume	-1		Most smartphones are still mass produced, such the iPhone 5S.
		Big part size		Small part size	1		Smartphones are smaller than 1.000 cm^3.
		Low complexity		High complexity	1		Many irregularities in the surface orientation, and contains many different components.
		Other material	Plastics		-1		A smartphone contains on average 42% metal, 33% plastic, and 25% other material (Ercan, 2013).
				Subtotal	**0**	**0%**	
Time	1						
Delivery lead time			Unimportance of customization	Importance of customization	1		Customization of the software and hardware is desired.
Rate of product introduction			Low innovation	High innovation	1		The smartphone market is highly innovative.
				Subtotal	**2**	**100%**	
Flexibility	1						
Customization			Unimportance of customization	Importance of customization	1		Customization of the software and hardware is desired.
Variety			Low variety	High variety	1		The variety in smartphone industry is fairly high.
Volume flexibility			Low demand uncertainty	High demand uncertainty	1		The smartphone market is considered volatile (Palm, Inc., 2010).
				Subtotal	**3**	**100%**	
				Total		2,25	
				% of max		**56,3%**	The maximum score is 4

Table I-5 Scoring of jewellery using the 3D Competitiveness Score Model

Tyres	Weight	Diminishment	← →	Improvement	% of max		Explanation
		-1	0	1			
Quality	1						
Performance			Unimportance of light weight	Importance of light weight	0		Weight is not an issue, since heaviness is associated with quality.
Features			Unimportance of ergonomics	Importance of ergonomics	1		Jewellery are regularly subject to physical contact.
Reliability		Importance of safety	Unimportance of safety		0		Jewellery do not have a safety requirement.
Conformance		High precision	Low precision		-1		High precision manufacturing is likely required due to the small size.
Durability		Long life cycle	Short life cycle		-1		The average life cycle of a high value necklace is assumed to be longer than 2 years.
Serviceability			Unimportance of service/maintenance	Importance of service/maintenance	0		Jewellery generally do not require repairs.
Aesthetics			Unimportance of aesthetics	Importance of aesthetics	1		Jewellery have an aesthetic function.
				Subtotal	**0**	**0%**	
Cost	1						
Production cost		High volume		Low volume	1		Jewellery is generally produced at a low volume, namely in the high value segment.
		Big part size		Small part size	1		Most jewellery is smaller than 1.000 cm³.
		Low complexity		High complexity	1		Jewellery can be considered having complex geometric forms.
		Other material	Plastics		-1		Most commonly used material in jewellery is likely gold.
				Subtotal	**2**	**66,7%**	
Time	1						
Delivery lead time			Unimportance of customization	Importance of customization	1		Jewellery is generally required to be unique, thus customization is desired.
Rate of product introduction			Low innovation	High innovation	0		Jewellery industry is not considered to be innovative.
				Subtotal	**1**	**50%**	
Flexibility	1						
Customization			Unimportance of customization	Importance of customization	1		Customization of the software and hardware is desired.
Variety			Low variety	High variety	1		The variety in the jewellery industry is fairly high.
Volume flexibility			Low demand uncertainty	High demand uncertainty	1		The jewellery market can be considered volatile, due to the high variety in products is forecasting difficult.
				Subtotal	**3**	**100%**	
				Total		2.167	
				% of max		54,2%	The maximum score is 4

Table I-6 Scoring of tyres using the 3D Competitiveness Score Model

Tyres	Weight	Diminishment ←		→ Improvement	% of max		Explanation
		-1	0	1			
Quality	1						
Performance			Unimportance of light weight	Importance of light weight	1		Weight reduction will result in better performing vehicles.
Features			Unimportance of ergonomics	Importance of ergonomics	0		Tyres do not require ergonomics.
Reliability		Importance of safety	Unimportance of safety		-1		Tyres have a safety requirement.
Conformance		High precision	Low precision		0		Tyres do not require high precision manufacturing.
Durability		Long life cycle	Short life cycle		-1		The lifespan of a tyre is about 50.000 km, which is about at least 4 years (Krömer, Kreipe, Reichenbach, & Stark, 1999).
Serviceability			Unimportance of service/maintenance	Importance of service/maintenance	0		Tyres generally do not require repairs.
Aesthetics			Unimportance of aesthetics	Importance of aesthetics	1		Tyres on consumer cars might have a decorative function.
				Subtotal	**0**	**0%**	
Cost	1						
Production cost		High volume		Low volume	-1		Michelin, one of the largest tyre manufacturers in the world, use mass production to make tyres (Michelin, 2014).
		Big part size		Small part size	-1		Tyres are usually larger than 1.000 cm³.
		Low complexity		High complexity	-1		The geometry of tyres can be considered fairly simple.
		Other material	Plastics		-1		Tyres consist of 47% rubber, 22% carbon black, 17-25% metal, and other materials (EER Limited, 2006).
				Subtotal	**-4**	**-100%**	
Time	1						
Delivery lead time			Unimportance of customization	Importance of customization	0		The variety in tyres is fairly large, however customization is usually not required.
Rate of product introduction			Low innovation	High innovation	0		The tyres industry can be considered not innovatie.
				Subtotal	**0**	**0%**	
Flexibility	1						
Customization			Unimportance of customization	Importance of customization	0		The variety in tyres is fairly large, however customization is usually not required.
Variety			Low variety	High variety	1		The variety in tyres is fairly large
Volume flexibility			Low demand uncertainty	High demand uncertainty	1		According to Michelin (2014), the tyre market is considered highly volatile, due to changing raw material and energy prices, and economic environment, and probably also due to its close ties to the volatile automotive industry.
				Subtotal	**2**	**66,7%**	
				Total		-0.333	
				% of max		-8,3%	The maximum score is 4

Table I-7 Scoring of glass using the 3D Competitiveness Score Model

Tyres	Weight	Diminishment ←	→	Improvement	% of max		Explanation
		-1	0	1			
Quality	1						
Performance			Unimportance of light weight	Importance of light weight	1		Glass container manufacturers aim to reduce weight of their products (The Gale Group, 2014).
Features			Unimportance of ergonomics	Importance of ergonomics	1		Glass containers are subject to physical contact.
Reliability		Importance of safety	Unimportance of safety		0		Glass containers usually do not have a safety requirement.
Conformance		High precision	Low precision		0		Glass containers do not require high accuracy production.
Durability		Long life cycle	Short life cycle		-1		Glass containers usually do not risk obsolescence within 2 years.
Serviceability			Unimportance of service/maintenance	Importance of service/maintenance	0		Glass containers do not require service.
Aesthetics			Unimportance of aesthetics	Importance of aesthetics	1		Glass containers often have a decorative function.
				Subtotal	**2**	**50%**	
Cost	1						
Production cost		High volume		Low volume	-1		Glass containers are usually produced at large quantities.
		Big part size		Small part size	1		Glass containers vary widely in size, here it will be assumed the average is smaller than 1.000 cm³.
		Low complexity		High complexity	-1		Glass containers usually have simple geometrical shapes, such as a cylinder or sphere (The Gale Group, 2014).
		Other material	Plastics		-1		
				Subtotal	**-2**	**-66,7%**	
Time	1						
Delivery lead time			Unimportance of customization	Importance of customization	0		The variety in glass containers is fairly large, however customization is usually not required.
Rate of product introduction			Low innovation	High innovation	0		The glass container market can be considered a mature market with low innovation (The Gale Group, 2014).
				Subtotal	**0**	**0%**	
Flexibility	1						
Customization			Unimportance of customization	Importance of customization	0		The variety in glass containers is fairly large, however customization is usually not required.
Variety			Low variety	High variety	1		The variety in glass containers is fairly large, however customization is usually not required.
Volume flexibility			Low demand uncertainty	High demand uncertainty	0		The glass container market can be considered a mature market (The Gale Group, 2014) and thus it is not volatile.
				Subtotal	**1**	**33,3%**	
				Total		0,166	
				% of max		**4,2%**	The maximum score is 4

Appendix J - Centralized and decentralized manufacturing

J.1 The evolution of manufacturing paradigms

The manufacturing paradigm has been transformed several times over the course of the last centuries (Figure J-2). It started with **craft production**, in which products were exactly created by skilled workers as demanded by the customer, one at a time (Koren, 2010). Later, in the beginning of the 20th century, Ford introduced **mass production** through dedicated manufacturing systems that allowed low-cost production at high volumes, but with limited product variety (Koren, 2010; Katel, 2012). And in the 80s, **mass customization** arose as a response to match society's demand for larger product variety. It offered multiple products variants in a low cost and high volume production environment, through customer involvement in the design process (co-design) and modularity of components (Duray, 2002; Kumar, 2004; Piller, Mass Customization: Reflections on the State of the Concept, 2004). As the trend shifts towards shorter product life cycles and more demand for personalised products (Mourtzis & Doukas, 2012), **personalised production** has been referred to as the next manufacturing paradigm (Koren, 2010; Mota, 2011). Whether it is a new paradigm is disputable, as the term has been used interchangeably with mass customization (Tseng & Hu, 2014; Kunze, 2008; Piller & Tseng, 2009). It can also simply be understood as the continuation of the mass customization paradigm, where customers have earlier or more influence with the co-design than before. 3DP fits into this paradigm, as it continues the trend of increased customization at low prices. It even allows consumers to design and manufacture something entirely independently. Given the rise of local printing services and domestic 3D printers, it can be said 3DP technology enables the democratization of manufacturing, and also the **decentralization of manufacturing**.

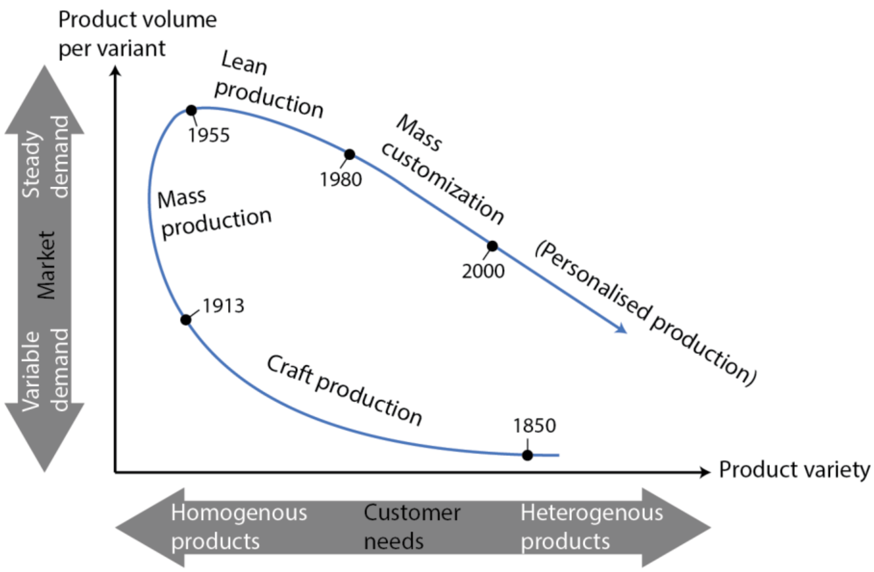


Figure J-1 The evolution of manufacturing paradigms, adapted from Koren (2010) and Mourtzis & Doukas (2012)

J.2 Centralized and decentralized manufacturing networks

Depending on the type of manufacturing, two fundamental types of value-added networks are established:

- A **centralized manufacturing (CM) network** is a production, distribution, and service network, in which a product is manufactured and serviced at a single location or through a chain of single locations, one location per operation (Schönsleben, 2007).
- A **decentralized manufacturing (DM) network** is a production, distribution, and service network, in which a product is manufactured, distributed and serviced at multiple locations that are as close to the customers as possible (Schönsleben, 2007).

Both CM and DM setups offer benefits. CM achieves advantages, such as economies of scale and consistent process quality (Schönsleben, 2007). On the other hand, DM competes with CM through better delivery times, lower transportation costs and higher agility. To determine which setup is most suitable, a firm needs to consider the cost structure, position in the industry value chains, and the competitive situation (Abele, Elzenheimer, Liebeck, & Meyer, 2006). Today, 51% of the manufacturers today in the U.S. still has a centralized manufacturing operation, 46% decentralized, and 3% of other type of operation (APQC, 2013).

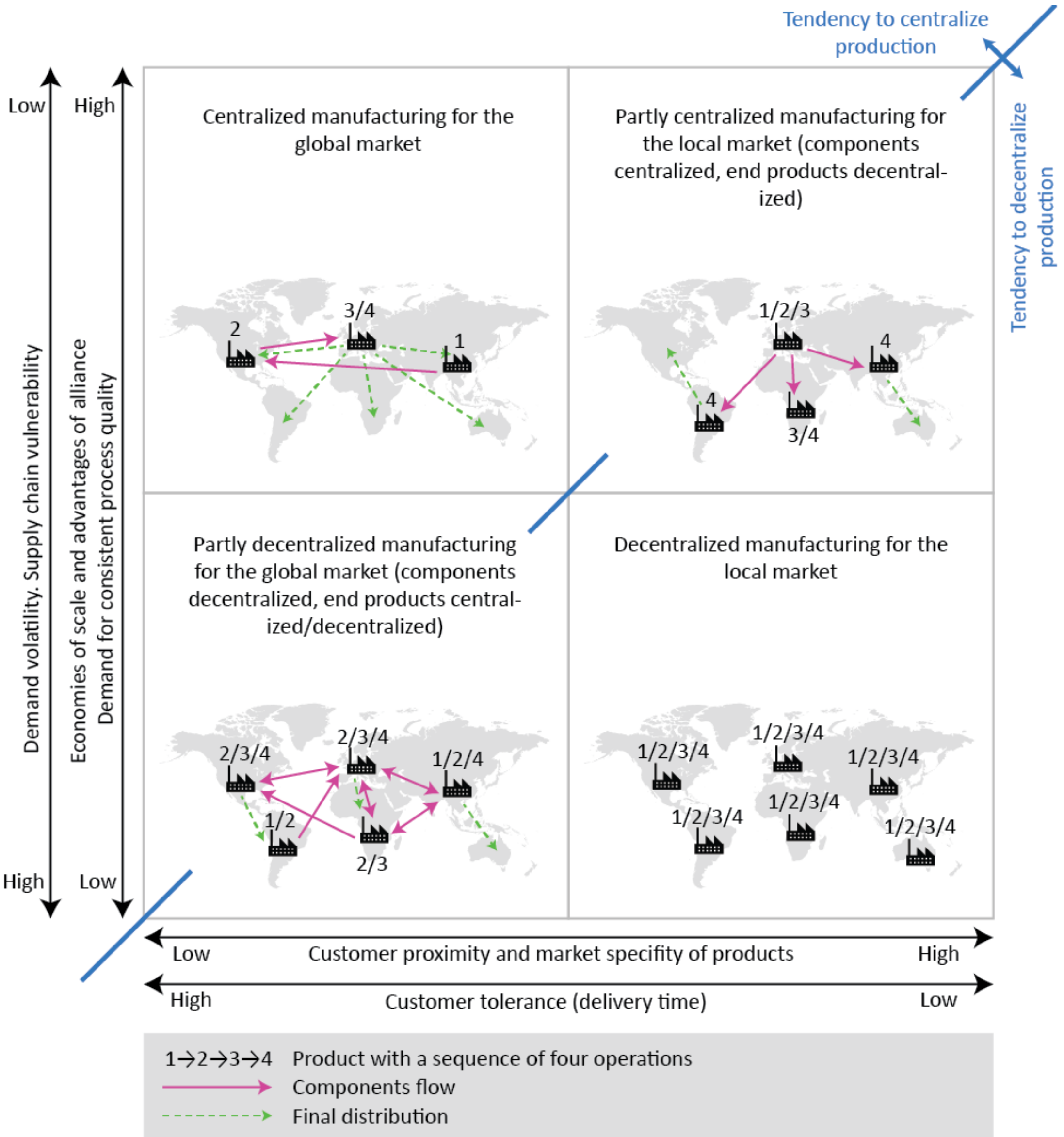


Figure J-2 Types of global manufacturing networks, modified from Schönsleben (2007)

Globalization has pushed firms to establish production facilities all over the world in order to stay competitive in a global market. The advantages of different geographical areas need to be considered, hence the firms have to decide on their manufacturing and distribution strategy, and whether to centralize or decentralize. Between the extreme positions of CM and DM, **hybrid strategies** exist (Figure J-2) (Abele, Elzenheimer, Liebeck, & Meyer, 2006; Schönsleben, 2007).

J.3 Centralized manufacturing for the global market

This strategy is beneficial where **economies of scale** are important and where strong and fixed partnerships are advantageous for the added value of the various production levels (Schönsleben, 2007). Hence a **consistent process quality** is easier to achieve. Distribution happens at the last production level. Precondition for this setup is a high customer tolerance for delivery time, and low vulnerability of the (only) supply chain (Schönsleben, 2007). It is usually exemplar for standard products, e.g. electronic components (LCD displays), consumer electronics, chemicals, and pharmaceuticals, fine chemicals, giant aircrafts, standard machines, and plants (Schönsleben, 2007).

J.4 Decentralized manufacturing for the local market

DM for the local market is advantageous when there is a requirement for **high proximity to customers, modification** for the local market, and when there is a low customers' tolerance for **delivery time** (Schönsleben, 2007). The supply chain should not be strongly dependent on economies of scale and should tolerate qualitative differences. Exemplary products are household appliances, building materials (gravel, cement), and products connected with services (Schönsleben, 2007).

J.5 Partly centralized manufacturing for the local market

This setup allows the final stage of the manufacturing process to be completed at decentralized locations (Schönsleben, 2007). When companies have a global customer base, they might opt to **locally finalize the products** based on the national requirements. This setup benefits from economies of scale resulting from the centralized execution of the initial manufacturing operations and proximity to market resulting from the local end production performed close to the customers. This is typical for consumer goods, which advocate "mass customization" (Schönsleben, 2007).

J.6 Partly decentralized manufacturing for the global market

Partly DM is when varied operations are performed at different locations and the product can be manufactured following **multiple possible paths** (Schönsleben, 2007). This approach is particularly useful in case of demand fluctuations or supply chain disruptions, as it provides flexibility in capacity. Products that suit this approach are standardized with high value density and sufficient customer tolerance with regard to delivery time, such as components or end products in the automotive industry, perishable foodstuffs, or important raw materials (e.g. steel) (Schönsleben, 2007).

Appendix K – Case studies of decentralization through 3DP

K.1 Dental implants industry

About 75-80% of restorative dental products (e.g. crowns and bridges) are made manually at global level as well as regional levels. Production at local level (at the dental practice, chairside) has been possible since 1987 using CEREC (Mörmann, 2006), a subtractive form of CADCAM (Computer Aided Design; Computer Aided Manufacturing) technology. Today, CADCAM can include subtractive (e.g. milling) as well as additive processes (e.g. 3DP). In combination with 3DP, CADCAM is becoming more advanced, capable of making a variety of products, e.g. crowns, bridges, diagnostic wax-ups, and other tooth-related objects (Dental Products Report, 2012).

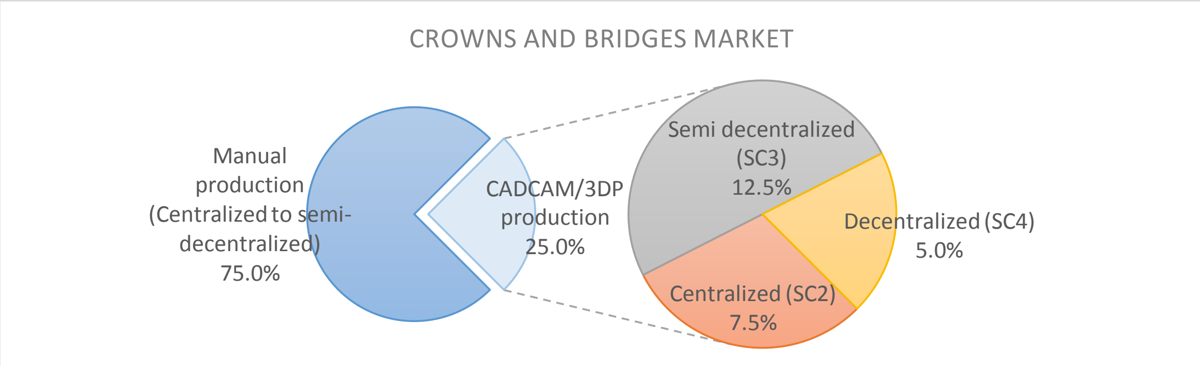


Figure K-1 Crowns and bridges market, in value terms (Straumann, 2013; Gart & Zamanian, 2009)

The market share for crowns and bridges production methods can be viewed in Figure K-1. The centralized CADCAM/3DP production generally corresponds with a SC2 type (7,5%), the in-lab production with a semi DM setup (SC3, 12,5%), and chairside production with DM setup (SC4, 5%). Manual production happens at centralized or semi decentralized locations, the division is unknown. With increasingly more capable 3D printers and a demand for faster turnaround times, the adoption of chairside production is increasing (Dental Lab Products, 2011). This is evidenced by the growth of CEREC sales (Sirona, 2013) and “increased competition from lab and chairside production” reported by the market leader, Straumann (2013).

K.2 Hearing aid industry

90% of all hearing aids today are produced with help of 3DP technology (Wile, 2013). The earpieces are usually 3D printed, while the electronics inside are inserted by a technician during the assembly. The finished products are sent to local audiologists where the customers receive their unit a few days after the initial fitting appointment.

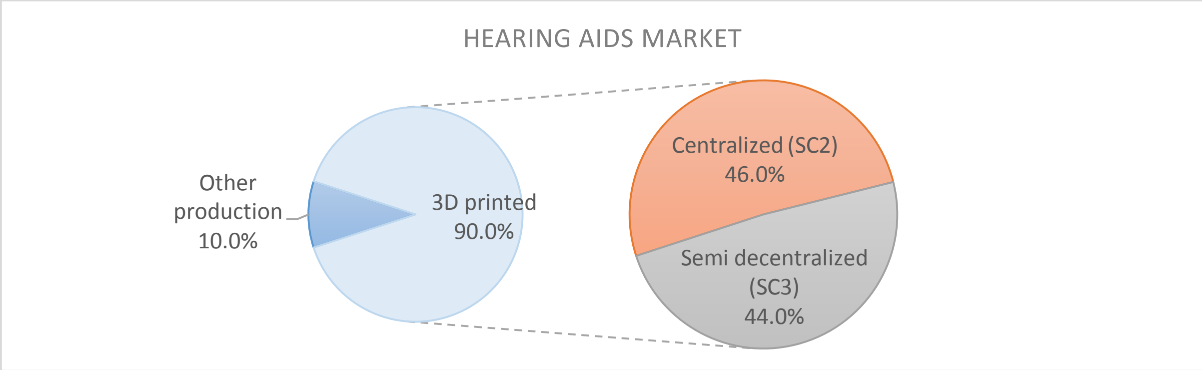


Figure K-2 Hearing aid market, in units terms, based on two hearing aid market leaders: William Demant Holding (2006) and Sonova (2014)

The production happens mostly through a CM (estimated 46%) or semi DM setup (estimated 44%) (SC2 or SC3) (Figure K-2). Local production (chairside production) does not exist yet. However, patents exist that are aimed at decentralizing the hearing aid production through 3DP to reduce customer waiting time (Brumback & Potter, 2007). This suggests the industry sees opportunity in improving its service through chairside production by using 3DP.

K.3 Other industries

No information has been found on the decentralization level of automotive, electronics or consumer goods industry in relation to 3DP market penetration. As for the automotive industry, due to the large size and complex nature of a car and the limited 3DP deployment for direct part production, decentralization in this industry is probably highly limited. Decentralization for electronics and consumer goods has been reported, such as jewellery. The total (semi-)decentralized production on a global scale is probably still below 2% in terms of units. And in the tyres and glass industry, that are still only prototyping with 3DP, probably no decentralization exist yet.

Appendix L - GDP growth factors and Global Innovation Index

Table L-1 GDP growth factors and Global Innovation Index (Van Diepen, 2011; Cornell University, INSEAD, and WIPO, 2014)

Country	% Annual GDP growth	Innovation Index	Country	% Annual GDP growth	Innovation Index
Aruba	1.1	5.00	Liberia	1	4.00
Afghanistan	5	4.00	Libyan Arab Jamahiriya	2.6	4.00
Angola	4	23.82	Saint Lucia	1.1	4.00
Anguilla	1.1	4.00	Liechtenstein	1.7	4.00
Aland Islands	2.2	4.00	Sri Lanka	3.2	28.98
Albania	1.3	30.47	Lesotho	-1.2	27.01
Andorra	1.3	4.00	Lithuania	2.2	41.00
Netherlands Antilles	4	4.00	Luxembourg	2.3	56.86
United Arab Emirates	2	43.25	Latvia	2.2	44.81
Argentina	1.8	35.13	Macao Special Administrative Region of China	3.4	4.00
Armenia	2	36.06	Saint-Martin	1.1	4.00
American Samoa	4	4.00	Morocco	2.9	32.24
Antigua and Barbuda	0.1	4.00	Monaco	1.6	4.00
Australia	2.7	55.01	Moldova	1.6	40.74
Austria	1.3	53.41	Madagascar	1.1	25.50
Azerbaijan	2	29.60	Maldives	2	4.00
Burundi	1.1	22.43	Mexico	1.7	36.02
Belgium	1.6	51.69	Marshall Islands	4	4.00
Benin	0.1	24.21	The former Yugoslav Republic of Macedonia	1.2	36.93
Burkina Faso	1	28.18	Mali	0.9	26.18
Bangladesh	3.4	24.35	Malta	1	50.44
Bulgaria	1.2	40.74	Myanmar	3.8	19.64
Bahrain	3.1	36.26	Montenegro	1.2	37.52
Bahamas	1.1	4.00	Mongolia	3.4	4.00
Bosnia and Herzegovina	1.3	32.43	Northern Mariana Islands	1.5	4.00
Saint-Barth,lemy	0.1	4.00	Mozambique	4.8	28.52
Belarus	1.6	37.10	Mauritania	1	4.00
Belize	1.6	4.00	Montserrat	1.1	37.01
Bermuda	2.6	4.00	Martinique	1.1	4.00
Bolivia	2.4	27.76	Mauritius	1.6	40.94
Brazil	2.5	36.29	Malawi	1.8	27.61
Barbados	0.1	40.78	Malaysia	5	45.60
Brunei Darussalam	4.8	31.67	Mayotte	1.1	4.00
Bhutan	3.8	31.83	Namibia	4	28.47
Botswana	1.8	30.87	New Caledonia	3.2	4.00
Central African Republic	0.2	4.00	Niger	1	24.27
Canada	2.4	56.13	Norfolk Island	4	4.00
Switzerland	1	4.00	Nigeria	4	27.79
Chile	1.8	40.64	Nicaragua	2.3	25.47
China	4.6	46.57	Niue	3	4.00
Cote d Ivoire	1	27.02	Netherlands	1.1	60.59
Cameroon	2.4	27.52	Norway	2.5	55.59
Democratic Republic of the Congo	3.2	4.00	Nepal	2.3	23.79
Congo	4.5	4.00	Nauru	4	4.00
Cook Islands	4	4.00	New Zealand	1	54.52
Colombia	1.9	35.50	Oman	2	33.87
Comoros	1.1	4.00	Pakistan	5	24.00
Cape Verde	1	30.09	Panama	2.8	38.30

Costa Rica	1.9	37.30	Pitcairn	4	4.00
Cuba	0.9	4.00	Peru	2.7	34.73
Cayman Islands	1.1	4.00	Philippines	4.5	29.87
Cyprus	3.1	45.82	Palau	4	4.00
Czech Republic	1.7	50.22	Papua New Guinea	4.1	4.00
Germany	1.7	56.02	Poland	1.8	40.64
Djibouti	0	4.00	Puerto Rico	1.1	4.00
Dominica	0.9	4.00	Democratic People s Republic of Korea	0	4.00
Denmark	1.6	57.52	Portugal	1.7	45.63
Dominican Republic	0.9	32.29	Paraguay	1.8	31.59
Algeria	2.9	24.20	Occupied Palestinian Territory	2	4.00
Ecuador	2.2	27.50	French Polynesia	4	4.00
Egypt	2.6	30.03	Qatar	2	40.31
Eritrea	1.1	4.00	R,union	1.1	4.00
Western Sahara	1	4.00	Romania	1.8	38.08
Spain	1.6	49.27	Moskva	-0.6	4.00
Estonia	2.2	51.54	Rwanda	0	29.31
Ethiopia	1.1	25.36	Saudi Arabia	2	41.61
Finland	2.1	61.67	Sudan	2.6	12.66
Fiji	4	30.39	Senegal	0.8	30.06
Falkland Islands	1.8	4.00	Singapore	3.3	59.24
France	1.6	52.18	Saint Helena	1	4.00
Faeroe Islands	2.2	4.00	Svalbard and Jan Mayen Islands	2.2	4.00
Micronesia Federated States of	4	4.00	Solomon Islands	4	4.00
Gabon	2.5	4.00	Sierra Leone	0.8	4.00
United Kingdom of Great Britain and Northern Ireland	2.1	62.37	El Salvador	-0.3	29.08
Georgia	2	34.53	San Marino	1.3	4.00
Guernsey	2.2	4.00	Somalia	1.1	4.00
Ghana	1	30.26	Saint Pierre and Miquelon	2.6	4.00
Gibraltar	1.3	4.00	Serbia	1.2	35.89
Guinea	1	20.25	Sao Tome and Principe	2.5	4.00
Guadeloupe	1.1	4.00	Suriname	1.8	4.00
Gambia	0.7	29.03	Slovakia	1.6	41.89
Guinea Bissau	0	4.00	Slovenia	1	47.23
Equatorial Guinea	2.5	4.00	Sweden	2	62.29
Greece	1.7	38.95	Swaziland	-0.4	25.33
Grenada	1.1	4.00	Seychelles	1.1	38.56
Greenland	2.6	4.00	Syrian Arab Republic	3.3	4.00
Guatemala	1.6	30.75	Turks and Caicos Islands	1.1	4.00
French Guiana	1.8	4.00	Chad	0.9	4.00
Guam	4	4.00	Togo	2.1	17.65
Guyana	-0.2	32.48	Thailand	4.7	39.28
Hong Kong Special Administrative Region of China	3.4	56.82	Tajikistan	1.6	23.73
Honduras	2.2	26.73	Tokelau	4	4.00
Croatia	1.2	40.75	Turkmenistan	1.6	4.00
Haiti	-0.3	4.00	Timor-Leste	4.8	4.00
Hungary	1.5	44.61	Tonga	4	4.00
Indonesia	4.5	31.81	Trinidad and Tobago	1.4	31.56
Isle of Man	2.1	4.00	Tunisia	2.1	32.94
India	4.5	33.70	Turkey	1.9	38.20
Ireland	3	56.67	Tuvalu	4	4.00

Iran Islamic Republic of	3	26.14	TAIWAN PROVINCE OF CHINA	3.4	55.27
Iraq	2	4.00	United Republic of Tanzania	1.3	4.00
Iceland	2.2	54.05	Uganda	1.1	31.14
Israel	-0.1	55.46	Ukraine	1.6	36.26
Italy	1	45.65	Uruguay	1.2	34.76
Jamaica	0.9	32.41	United States of America	2.8	60.09
Jersey	2.1	4.00	Uzbekistan	1.6	25.20
Jordan	0.7	36.21	Saint Vincent and the Grenadines	1.2	4.00
Japan	1.5	52.41	Venezuela Bolivarian Republic of	2.1	25.66
Kazakhstan	1.6	32.75	British Virgin Islands	4	4.00
Kenya	1.3	31.85	United States Virgin Islands	1.1	4.00
Kyrgyzstan	1.6	27.75	Viet Nam	4.8	34.89
Cambodia	4.8	28.66	Vanuatu	4	4.00
Kiribati	4	4.00	Wallis and Futuna Islands	4	4.00
Saint Kitts and Nevis	1.1	4.00	Samoa	4	4.00
Republic of Korea	4.1	55.27	Yemen	4.2	19.53
Kuwait	1.8	35.19	South Africa	1.6	38.25
Lao People s Democratic Republic	4.8	4.00	Zambia	6.7	25.76
Lebanon	2	33.60	Zimbabwe	4.5	24.31

Appendix M Containerization per NSTR group

Table M-1 Import and export, containerization and average weight of NSTR groups (CBS, 2007; Eurostat, 2014b)

NSTR	Import and export EU28 in 2013 (tons) (Eurostat, 2014b)	Containerization rate (CBS, 2007)	Average TEU weight excluding container weight (tons)
Total		11,3	
0 Landbouwproducten;levende dieren	97 041 935	54,0	16,1
00 Levende dieren		0,0	
01 Granen		22,3	
02 Aardappelen		12,6	
03 Vers fruit; groenten		66,3	
04 Textielstoffen en -afval		100,0	
05 Hout en kurk		44,7	
09 Andere ruwe producten		98,5	
1 Voedingsproducten en veevoeder	113 609 151	24,0	15,6
11 Suiker		5,9	
12 Dranken		100,0	
13 Genotmiddelen en specerijen		80,0	
14 Vlees, vis en zuivel;spijsvetten		94,4	
16 Graan-,fruit-,groentebereidingen		70,7	
17 Veevoeder; voedingsmiddelenafval		2,0	
18 Oliehoudende zaden; oliën,vetten		3,5	
2 Vaste minerale brandstoffen	178 517 729	0,3	12,8
21 Steenkool		0,1	
22 Bruinkool en turf		20,3	
23 Cokes		1,1	
3 Aardolie en aardolieproducten	724 477 559	0,1	10,8
31 Ruwe aardolie		0,0	
32 Vloeibare brandstoffen		0,0	
33 Energiegassen		0,1	
34 Andere aardoliederivaten		2,6	
4 Ertsen en metaalresiduen	146 476 695	0,7	17,3
41 IJzererts		0,0	
45 Andere ertsen;non-ferro residuen		5,6	
46 Schroot en hoogovenresiduen		24,5	
5 Metalen, metalen halffabrikaten	65 579 814	25,5	20,1
51 Ruw ijzer,staal; ferrolegeringen		32,9	
52 Halffabrikaten van ferrometaal		3,1	
53 Staaf- en vormstaal;draad, rails		46,0	
54 Platen en banden van ijzer,staal		15,6	
55 Gieterijproducten (ijzer,staal)		87,3	
56 Non-ferrometalen,-halffabrikaten		29,3	
6 Ruwe mineralen; bouwmaterialen	88 291 385	19,1	19,4
61 Zand, grind, klei en slakken		3,6	
62 Zout,ongeroost ijzerkies, zwavel		23,0	
63 Andere ruwe mineralen		6,9	
64 Cement, kalk		19,5	
65 Gips		2,3	
69 Bewerkte bouwmaterialen		53,4	
7 Meststoffen	23 778 873	1,0	22,8
71 Natuurlijke meststoffen		0,0	
72 Kunstmeststoffen		1,6	
8 Chemische producten	103 307 752	19,6	14,3
81 Chemische basisproducten		8,9	
82 Aluminiumoxide en -hydroxide		2,8	

83 Benzol; teer e.d. ruwe producten		2,9	
84 Cellulose en papierafval		31,6	
89 Andere chemische producten		73,0	
9 Overige goederen en fabrikaten	146 125 544	57,5	8,9
91 Vervoermaterieel		77,6	
92 Landbouwtraktoren en -machines		97,8	
93 Apparaten, motoren, ov. machines		84,1	
94 Metaalfabrikaten		92,2	
95 Glas(werk), keramische producten		97,0	
96 Leer, schoeisel; textiel,kleding		100,0	
97 Andere (half)fabrikaten (elekronica en huisraad)		77,1	
99 Overige goederen (w.o.stukgoed)		13,0	

Table M-2 NSTR 9 detailed information (Eurostat, 2014b; CBS, 2007)

NSTR	Description	Import-export EU28 (Tons)	%	Containe-rization rate	TEUs	%
9	**Vehicles, machinery and other manufactured goods**			57,5		
91	**Transportation equipment**			77,6		
910	Transport equipment, whether or not assembled parts thereof	10 456 838	8.0%		675 610	7.4%
92	**Agricultural tracts and machinery**		0.0%	97,8		0.0%
920	Agricultural tracts and equipment, whether or not assembled parts thereof	875 945	0.7%		56 594	0.6%
93	**Electric and other machinery, apparatus**		0.0%	84,1		0.0%
931	Electric machinery, apparatus, engines	12 000 063	9.2%		775 317	8.5%
939	Non-electric machinery, apparatus	12 138 955	9.3%		784 291	8.6%
94	**Manufactures of material**		0.0%	92,2		0.0%
941	Finished structural parts of metal	9 538 962	7.3%		616 307	6.7%
949	Other manufactures of metal	4 633 514	3.6%		299 369	3.3%
95	**Glass, glassware and ceramic products**		0.0%	97,0		0.0%
951	Glass	943 862	0.7%		60 982	0.7%
952	Glassware, pottery, and other manufactures of minerals	2 886 328	2.2%		186 484	2.0%
96	**Leather, textiles and garments**		0.0%	100,0		0.0%
961	Leather and furs	879 092	0.7%		98 774	1.1%
962	Textile yarn, fabrics, made-up articles and related products	7 781 655	6.0%		874 343	9.5%
963	Clothing and footwear	9 274 269	7.1%		1 042 053	11.4%
97	**Other finished and semi manufactured products**		0.0%	77,1		0.0%
971	Finished and semi manufactured rubber products	3 630 535	2.8%		314 510	3.4%
972	Paper and cardboard	4 819 193	3.7%		417 483	4.6%
973	Paper and cardboard manufactures	4 109 232	3.2%		355 980	3.9%
974	Paper matter	440 675	0.3%		38 175	0.4%
975	Furniture, new	7 103 137	5.5%		615 339	6.7%
976	Wood and cork manufactures, excluding furniture	6 998 758	5.4%		606 297	6.6%
979	Other manufactured articles	12 232 663	9.4%		1 059 706	11.6%
99	**Miscellaneous articles**		0.0%	13,0		0.0%
991	Packing containers, used	-	0.0%		-	0.0%
992	Construction materials, used	-	0.0%		-	0.0%
993	Removal equipment	-	0.0%		-	0.0%

994	Pearls, precious stones, precious metals (gold), coins	2 148	0.0%	31	0.0%
999	Other manufactured goods	19 474 225	15.0%	284 455	3.1%
9	**Total**	**130 220 049**	100.0%	**9 162 102**	100.0%

Appendix N - World Container Model logit choice model formulas

N.1 Logit choice model

Logit model extended with path size overlap in the World Container Model (Tavasszy, Minderhoud, Perrin, & Notteboom, 2011):

$$P_r = \frac{e^{-\mu(C_r + \ln S_r)}}{\sum_{hCS} e^{-\mu(C_r + \ln S_r)}}$$

With the path size overlap defined as:

$$S_r = \sum_{a \in \Gamma_r} \left(\frac{Z_a}{Z_r}\right) \frac{1}{N_{ah}}$$

Where:

P_r	Probability of route r
CS	Choice set
μ	Logit scale parameter
a	Link in route r
Γ_r	Set of links in route r
Z_a	Length of link a
Z_n	Length of route r
N_{ah}	Number of times link a is found in alternative routes

The generalized cost function is defined as:

$$C_r = \sum_{p \in r} A_p + \sum_{l \in r} C_l + \alpha \left(\sum_{p \in r} T_p + \sum_{l \in r} t_l \right)$$

Where:

P	Ports used by the route
l	Links used by the route
A_p	Total cost of transhipment at port p
C_l	Total cost of transportation of link l
T_p	Time spent during transhipment at port p
T_l	Time spent during transportation over link l
α	Value of transport time (USD/day/ton)

N.2 Gravity model

The general gravity model for estimating GDP growth:

$$ln\ T_{ij} = \beta_0 + \beta_1 \ln Y_i + \beta_2 \ln Y_j + \beta_3 \ln y_i + \beta_4 \ln y_j + \beta_5 \ln D_{ij} + \beta_6 Adj_{ij} + \beta_7 Lang_{ij} + \beta_8 PTA_{ij} + \beta_9 Religion_{ij} + \beta_{10} Col_{ij}$$

Where:

T_{ij}	Aggregate merchandise exports from country i to j

Y_i	Total GDP for country i
y_i	GDP per capita for country i
D_{ij}	Distance between countries i and j
Adj_{ij}	Border between i and j
$Lang_{ij}$	Similarity of primary language between i and j
PTA_{ij}	Preferential Trade Agreement between i and j
$Religion_{ij}$	Religious similarity between i and j
Col_{ij}	Colonial history between i and j

Appendix O - Scoring of NSTR 9 products

Table O-1 Scoring of NSTR 9 sub-groups using the 3DCSM and the decentralization level

910 Transport equipment	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	25.0%	62.5%	81.3%	100.0%	0.0%
Performance	1	1	1	1	0
Features	1	1	1	1	0
Reliability	-1	-0.5	-0.25	0	0
Conformance	-1	-0.5	-0.25	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	1	1	1	1	0
Aesthetics	1	1	1	1	0
Cost	-66.7%	-64.7%	-28.7%	-22.7%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	-1	-0.97	-0.93	-0.84	0
0	1	1	1	1	0
0	-1	-1	0	0	0
Time	100.0%	100.0%	100.0%	100.0%	0.0%
Delivery speed	1	1	1	1	0
Development speed	1	1	1	1	0
Flexibility	100.0%	100.0%	100.0%	100.0%	0.0%
Customization	1	1	1	1	0
Variety	1	1	1	1	0
Volume flexibility	1	1	1	1	0
3DSCM score	39.6%	49.5%	63.1%	69.3%	100.0%
DM level	0.7%	2.4%	8.3%	13.4%	88.1%

920 Agricultural tracts and machinery	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	0.0%	37.5%	56.3%	75.0%	0.0%
Performance	1	1	1	1	0
Features	1	1	1	1	0
Reliability	-1	-0.5	-0.25	0	0
Conformance	-1	-0.5	-0.25	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	1	1	1	1	0
Aesthetics	0	0	0	0	0
Cost	0.0%	1.0%	35.7%	38.7%	0.0%
Production cost	1	1	1	1	0
0	-1	-0.97	-0.93	-0.84	0
0	1	1	1	1	0
0	-1	-1	0	0	0
Time	100.0%	100.0%	100.0%	100.0%	0.0%
Delivery speed	1	1	1	1	0
Development speed	1	1	1	1	0
Flexibility	100.0%	100.0%	100.0%	100.0%	0.0%
Customization	1	1	1	1	0
Variety	1	1	1	1	0
Volume flexibility	1	1	1	1	0
3DSCM score	50.0%	59.6%	73.0%	78.4%	100.0%
DM level	2.5%	6.2%	17.4%	25.2%	88.1%

931 Electric and other machinery, apparatus	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	-25.0%	12.5%	31.3%	50.0%	0.0%
Performance	1	1	1	1	0
Features	0	0	0	0	0
Reliability	-1	-0.5	-0.25	0	0

939 Non-electric and other machinery, apparatus	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	-25.0%	12.5%	31.3%	50.0%	0.0%
Performance	1	1	1	1	0
Features	0	0	0	0	0
Reliability	-1	-0.5	-0.25	0	0

Conformance	-1	-0.5	-0.25	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	1	1	1	1	0
Aesthetics	0	0	0	0	0
Cost	0.0%	1.0%	35.7%	38.7%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	1	1	1	1	0
0	1	1	1	1	0
0	-1	-1	0	0	0
Time	50.0%	50.0%	50.0%	50.0%	0.0%
Delivery speed	0	0	0	0	0
Development speed	1	1	1	1	0
Flexibility	66.7%	66.7%	66.7%	66.7%	0.0%
Customization	0	0	0	0	0
Variety	1	1	1	1	0
Volume flexibility	1	1	1	1	0
3DSCM score	**22.9%**	**32.5%**	**45.9%**	**51.3%**	**100.0%**
DM level	**0.0%**	**0.3%**	**1.6%**	**2.8%**	**88.1%**

Conformance	-1	-0.5	-0.25	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	1	1	1	1	0
Aesthetics	0	0	0	0	0
Cost	-66.7%	-64.7%	-28.7%	-22.7%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	-1	-0.97	-0.93	-0.84	0
0	1	1	1	1	0
0	-1	-1	0	0	0
Time	50.0%	50.0%	50.0%	50.0%	0.0%
Delivery speed	0	0	0	0	0
Development speed	1	1	1	1	0
Flexibility	66.7%	66.7%	66.7%	66.7%	0.0%
Customization	0	0	0	0	0
Variety	1	1	1	1	0
Volume flexibility	1	1	1	1	0
3DSCM score	**6.3%**	**16.1%**	**29.8%**	**36.0%**	**100.0%**
DM level	**0.0%**	**0.0%**	**0.2%**	**0.5%**	**88.1%**

941 Finished structural parts of metal					
	Present	**Sc. L**	**Sc. B**	**Sc. H**	**Sc. X**
Quality	0.0%	25.0%	37.5%	50.0%	0.0%
Performance	1	1	1	1	0
Features	0	0	0	0	0
Reliability	-1	-0.5	-0.25	0	0
Conformance	0	0	0	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	0	0	0	0	0
Aesthetics	1	1	1	1	0
Cost	-133.3%	-98.0%	-62.0%	-56.0%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	-1	-0.97	-0.93	-0.84	0
0	-1	0	0	0	0

949 Other manufactures of metal					
	Present	**Sc. L**	**Sc. B**	**Sc. H**	**Sc. X**
Quality	25.0%	37.5%	43.8%	50.0%	0.0%
Performance	1	1	1	1	0
Features	0	0	0	0	0
Reliability	0	0	0	0	0
Conformance	0	0	0	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	0	0	0	0	0
Aesthetics	1	1	1	1	0
Cost	-133.3%	-98.0%	-62.0%	-56.0%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	-1	-0.97	-0.93	-0.84	0
0	-1	0	0	0	0

	Present	Sc. L	Sc. B	Sc. H	Sc. X
0	-1	-1	0	0	0
Time	0.0%	0.0%	0.0%	0.0%	0.0%
Delivery speed	0	0	0	0	0
Development speed	0	0	0	0	0
Flexibility	0.0%	0.0%	0.0%	0.0%	0.0%
Customization	0	0	0	0	0
Variety	0	0	0	0	0
Volume flexibility	0	0	0	0	0
3DSCM score	**-33.3%**	**-18.3%**	**-6.1%**	**-1.5%**	**100.0%**
DM level	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**88.1%**

	Present	Sc. L	Sc. B	Sc. H	Sc. X
0	-1	-1	0	0	0
Time	0.0%	0.0%	0.0%	0.0%	0.0%
Delivery speed	0	0	0	0	0
Development speed	0	0	0	0	0
Flexibility	66.7%	66.7%	66.7%	66.7%	0.0%
Customization	0	0	0	0	0
Variety	1	1	1	1	0
Volume flexibility	1	1	1	1	0
3DSCM score	**-10.4%**	**1.5%**	**12.1%**	**15.2%**	**100.0%**
DM level	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**88.1%**

951 Glass	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	25.0%	37.5%	43.8%	50.0%	0.0%
Performance	1	1	1	1	0
Features	0	0	0	0	0
Reliability	0	0	0	0	0
Conformance	0	0	0	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	0	0	0	0	0
Aesthetics	1	1	1	1	0
Cost	-133.3%	-98.0%	-95.3%	-89.3%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	-1	-0.97	-0.93	-0.84	0
0	-1	0	0	0	0
0	-1	-1	-1	-1	0
Time	0.0%	0.0%	0.0%	0.0%	0.0%
Delivery speed	0	0	0	0	0
Development speed	0	0	0	0	0
Flexibility	0.0%	0.0%	0.0%	0.0%	0.0%
Customization	0	0	0	0	0
Variety	0	0	0	0	0
Volume flexibility	0	0	0	0	0

952 Glassware, pottery and other manufactures of minerals	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	50.0%	62.5%	68.8%	75.0%	0.0%
Performance	1	1	1	1	0
Features	1	1	1	1	0
Reliability	0	0	0	0	0
Conformance	0	0	0	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	0	0	0	0	0
Aesthetics	1	1	1	1	0
Cost	-66.7%	-32.3%	-31.0%	5.3%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	1	1	1	1	0
0	-1	0	0	0	0
0	-1	-1	-1	0	0
Time	0.0%	0.0%	0.0%	0.0%	0.0%
Delivery speed	0	0	0	0	0
Development speed	0	0	0	0	0
Flexibility	66.7%	66.7%	66.7%	66.7%	0.0%
Customization	0	0	0	0	0
Variety	1	1	1	1	0
Volume flexibility	1	1	1	1	0

3DSCM score	-27.1%	-15.1%	-12.9%	-9.8%	100.0%
DM level	0.0%	0.0%	0.0%	0.0%	88.1%

961 Leather and furs					
	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	25.0%	37.5%	43.8%	50.0%	50.0%
Performance	0	0	0	0	0
Features	1	1	1	1	1
Reliability	0	0	0	0	0
Conformance	0	0	0	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	0	0	0	0	0
Aesthetics	1	1	1	1	1
Cost	-66.7%	-64.7%	-62.0%	-56.0%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	-1	-0.97	-0.93	-0.84	0
0	1	1	1	1	1
0	-1	-1	-1	-1	-1
Time	100.0%	100.0%	100.0%	100.0%	100.0%
Delivery speed	1	1	1	1	1
Development speed	1	1	1	1	1
Flexibility	66.7%	66.7%	66.7%	66.7%	66.7%
Customization	0	0	0	0	0
Variety	1	1	1	1	1
Volume flexibility	1	1	1	1	1
3DSCM score	31.3%	34.9%	37.1%	40.2%	54.2%
DM level	0.2%	0.4%	0.5%	0.8%	3.8%

963 Clothing and footwear					
	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	50.0%	50.0%	50.0%	50.0%	50.0%
Performance	0	0	0	0	0
Features	1	1	1	1	1

3DSCM score	12.5%	24.2%	26.1%	36.8%	100.0%
DM level	0.0%	0.1%	0.1%	0.5%	88.1%

962 Textile yarn, fabrics, made-up articles and related products					
	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	25.0%	37.5%	43.8%	50.0%	50.0%
Performance	0	0	0	0	0
Features	1	1	1	1	1
Reliability	0	0	0	0	0
Conformance	0	0	0	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	0	0	0	0	0
Aesthetics	1	1	1	1	1
Cost	-66.7%	-64.7%	-62.0%	-56.0%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	-1	-0.97	-0.93	-0.84	0
0	1	1	1	1	1
0	-1	-1	-1	-1	-1
Time	100.0%	100.0%	100.0%	100.0%	100.0%
Delivery speed	1	1	1	1	1
Development speed	1	1	1	1	1
Flexibility	66.7%	66.7%	66.7%	66.7%	66.7%
Customization	0	0	0	0	0
Variety	1	1	1	1	1
Volume flexibility	1	1	1	1	1
3DSCM score	31.3%	34.9%	37.1%	40.2%	54.2%
DM level	0.2%	0.4%	0.5%	0.8%	3.8%

971 Finished and semimanifactured rubber products					
	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	25.0%	37.5%	43.8%	50.0%	0.0%
Performance	0	0	0	0	0
Features	1	1	1	1	0

	Present	Sc. L	Sc. B	Sc. H	Sc. X
Reliability	0	0	0	0	0
Conformance	0	0	0	0	0
Durability	0	0	0	0	0
Serviceability	0	0	0	0	0
Aesthetics	1	1	1	1	1
Cost	0.0%	1.0%	2.3%	5.3%	33.3%
Production cost	1	1	1	1	1
0	-1	-0.97	-0.93	-0.84	0
0	1	1	1	1	1
0	-1	-1	-1	-1	-1
Time	100.0%	100.0%	100.0%	100.0%	100.0%
Delivery speed	1	1	1	1	1
Development speed	1	1	1	1	1
Flexibility	100.0%	100.0%	100.0%	100.0%	100.0%
Customization	1	1	1	1	1
Variety	1	1	1	1	1
Volume flexibility	1	1	1	1	1
3DSCM score	**62.5%**	**62.8%**	**63.1%**	**63.8%**	**70.8%**
DM level	**7.8%**	**8.0%**	**8.2%**	**8.7%**	**14.9%**

	Present	Sc. L	Sc. B	Sc. H	Sc. X
Reliability	0	0	0	0	0
Conformance	0	0	0	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	0	0	0	0	0
Aesthetics	1	1	1	1	0
Cost	0.0%	1.0%	2.3%	5.3%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	1	1	1	1	0
0	1	1	1	1	0
0	-1	-1	-1	-1	0
Time	0.0%	0.0%	0.0%	0.0%	0.0%
Delivery speed	0	0	0	0	0
Development speed	0	0	0	0	0
Flexibility	66.7%	66.7%	66.7%	66.7%	0.0%
Customization	0	0	0	0	0
Variety	1	1	1	1	0
Volume flexibility	1	1	1	1	0
3DSCM score	**22.9%**	**26.3%**	**28.2%**	**30.5%**	**100.0%**
DM level	**0.0%**	**0.1%**	**0.1%**	**0.2%**	**88.1%**

972 Paper and cardboard	**Present**	**Sc. L**	**Sc. B**	**Sc. H**	**Sc. X**
Quality	-25.0%	-12.5%	-6.3%	0.0%	0.0%
Performance	0	0	0	0	0
Features	0	0	0	0	0
Reliability	0	0	0	0	0
Conformance	0	0	0	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	0	0	0	0	0
Aesthetics	0	0	0	0	0
Cost	-66.7%	-32.3%	-31.0%	-28.0%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	1	1	1	1	1

973 Paper and cardboard manufactured	**Present**	**Sc. L**	**Sc. B**	**Sc. H**	**Sc. X**
Quality	0.0%	12.5%	18.8%	25.0%	25.0%
Performance	0	0	0	0	0
Features	0	0	0	0	0
Reliability	0	0	0	0	0
Conformance	0	0	0	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	0	0	0	0	0
Aesthetics	1	1	1	1	1
Cost	-66.7%	-32.3%	-31.0%	-28.0%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	1	1	1	1	1

0	-1	0	0	0	0
0	-1	-1	-1	-1	-1
Time	0.0%	0.0%	0.0%	0.0%	0.0%
Delivery speed	0	0	0	0	0
Development speed	0	0	0	0	0
Flexibility	0.0%	0.0%	0.0%	0.0%	0.0%
Customization	0	0	0	0	0
Variety	0	0	0	0	0
Volume flexibility	0	0	0	0	0
3DSCM score	**-22.9%**	**-11.2%**	**-9.3%**	**-7.0%**	**0.0%**
DM level	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**

0	-1	0	0	0	0
0	-1	-1	-1	-1	-1
Time	0.0%	0.0%	0.0%	0.0%	0.0%
Delivery speed	0	0	0	0	0
Development speed	0	0	0	0	0
Flexibility	33.3%	33.3%	33.3%	33.3%	33.3%
Customization	0	0	0	0	0
Variety	1	1	1	1	1
Volume flexibility	0	0	0	0	0
3DSCM score	**-8.3%**	**3.4%**	**5.3%**	**7.6%**	**14.6%**
DM level	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**

974 Paper matter					
	Present	**Sc. L**	**Sc. B**	**Sc. H**	**Sc. X**
Quality	0.0%	12.5%	18.8%	25.0%	25.0%
Performance	0	0	0	0	0
Features	0	0	0	0	0
Reliability	0	0	0	0	0
Conformance	0	0	0	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	0	0	0	0	0
Aesthetics	1	1	1	1	1
Cost	-66.7%	-32.3%	-31.0%	-28.0%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	1	1	1	1	1
0	-1	0	0	0	0
0	-1	-1	-1	-1	-1
Time	0.0%	0.0%	0.0%	0.0%	0.0%
Delivery speed	0	0	0	0	0
Development speed	0	0	0	0	0
Flexibility	0.0%	0.0%	0.0%	0.0%	0.0%
Customization	0	0	0	0	0
Variety	0	0	0	0	0

975 Furniture, new					
	Present	**Sc. L**	**Sc. B**	**Sc. H**	**Sc. X**
Quality	50.0%	50.0%	50.0%	50.0%	0.0%
Performance	0	0	0	0	0
Features	1	1	1	1	0
Reliability	0	0	0	0	0
Conformance	0	0	0	0	0
Durability	0	0	0	0	0
Serviceability	0	0	0	0	0
Aesthetics	1	1	1	1	0
Cost	0.0%	1.0%	2.3%	5.3%	0.0%
Production cost	1	1	1	1	0
0	-1	-0.97	-0.93	-0.84	0
0	1	1	1	1	0
0	-1	-1	-1	-1	0
Time	100.0%	100.0%	100.0%	100.0%	0.0%
Delivery speed	1	1	1	1	0
Development speed	1	1	1	1	0
Flexibility	100.0%	100.0%	100.0%	100.0%	0.0%
Customization	1	1	1	1	0
Variety	1	1	1	1	0

Volume flexibility	0	0	0	0	0
3DSCM score	**-16.7%**	**-5.0%**	**-3.1%**	**-0.7%**	**6.3%**
DM level	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**

976 Wood and cork manufactures, excluding furniture

	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	0.0%	12.5%	18.8%	25.0%	25.0%
Performance	0	0	0	0	0
Features	0	0	0	0	0
Reliability	0	0	0	0	0
Conformance	0	0	0	0	0
Durability	-1	-0.5	-0.25	0	0
Serviceability	0	0	0	0	0
Aesthetics	1	1	1	1	1
Cost	-133.3%	-98.0%	-95.3%	-89.3%	-33.3%
Production cost	-1	-0.97	-0.93	-0.84	0
0	-1	-0.97	-0.93	-0.84	0
0	-1	0	0	0	0
0	-1	-1	-1	-1	-1
Time	0.0%	0.0%	0.0%	0.0%	0.0%
Delivery speed	0	0	0	0	0
Development speed	0	0	0	0	0
Flexibility	33.3%	33.3%	33.3%	33.3%	33.3%
Customization	0	0	0	0	0
Variety	1	1	1	1	1
Volume flexibility	0	0	0	0	0
3DSCM score	**-25.0%**	**-13.0%**	**-10.8%**	**-7.8%**	**6.3%**
DM level	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**

994 Pearls, precious stones, precious metals (gold), coins

	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	25.0%	37.5%	43.8%	50.0%	0.0%
Performance	0	0	0	0	0

Volume flexibility	1	1	1	1	0
3DSCM score	**62.5%**	**62.8%**	**63.1%**	**63.8%**	**100.0%**
DM level	**7.8%**	**8.0%**	**8.2%**	**8.7%**	**88.1%**

979 Other manufactured articles

	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	75.0%	75.0%	75.0%	75.0%	0.0%
Performance	1	1	1	1	0
Features	1	1	1	1	0
Reliability	0	0	0	0	0
Conformance	0	0	0	0	0
Durability	0	0	0	0	0
Serviceability	0	0	0	0	0
Aesthetics	1	1	1	1	0
Cost	-100.0%	-64.7%	-62.0%	-56.0%	0.0%
Production cost	-1	-0.97	-0.93	-0.84	0
0	-1	-0.97	-0.93	-0.84	0
0	-1	0	0	0	0
0	0	0	0	0	0
Time	0.0%	0.0%	0.0%	0.0%	0.0%
Delivery speed	0	0	0	0	0
Development speed	0	0	0	0	0
Flexibility	66.7%	66.7%	66.7%	66.7%	0.0%
Customization	0	0	0	0	0
Variety	1	1	1	1	0
Volume flexibility	1	1	1	1	0
3DSCM score	**10.4%**	**19.3%**	**19.9%**	**21.4%**	**100.0%**
DM level	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**88.1%**

999 Other manufactured goods

	Present	Sc. L	Sc. B	Sc. H	Sc. X
Quality	75.0%	75.0%	75.0%	75.0%	0.0%
Performance	1	1	1	1	0

Features		1	1	1	1	0
Reliability		0	0	0	0	0
Conformance		0	0	0	0	0
Durability		-1	-0.5	-0.25	0	0
Serviceability		0	0	0	0	0
Aesthetics		1	1	1	1	0
Cost		100.0%	100.0%	100.0%	100.0%	0.0%
Production cost		1	1	1	1	0
	0	1	1	1	1	0
	0	1	1	1	1	0
	0	0	0	0	0	0
Time		0.0%	0.0%	0.0%	0.0%	0.0%
Delivery speed		0	0	0	0	0
Development speed		0	0	0	0	0
Flexibility		100.0%	100.0%	100.0%	100.0%	0.0%
Customization		1	1	1	1	0
Variety		1	1	1	1	0
Volume flexibility		1	1	1	1	0
3DSCM score		**56.3%**	**59.4%**	**60.9%**	**62.5%**	**100.0%**
DM level		**4.6%**	**6.0%**	**6.9%**	**7.8%**	**88.1%**

Features		1	1	1	1	0
Reliability		0	0	0	0	0
Conformance		0	0	0	0	0
Durability		0	0	0	0	0
Serviceability		0	0	0	0	0
Aesthetics		1	1	1	1	0
Cost		-33.3%	1.0%	2.3%	5.3%	0.0%
Production cost		-1	-0.97	-0.93	-0.84	0
	0	1	1	1	1	0
	0	-1	0	0	0	0
	0	0	0	0	0	0
Time		0.0%	0.0%	0.0%	0.0%	0.0%
Delivery speed		0	0	0	0	0
Development speed		0	0	0	0	0
Flexibility		66.7%	66.7%	66.7%	66.7%	0.0%
Customization		0	0	0	0	0
Variety		1	1	1	1	0
Volume flexibility		1	1	1	1	0
3DSCM score		**27.1%**	**35.7%**	**36.0%**	**36.8%**	**100.0%**
DM level		**0.1%**	**0.4%**	**0.5%**	**0.5%**	**88.1%**

Appendix P 3DCSM scores and decentralization levels of NSTR 9 products

Figure P-1 3DCSM scores and decentralization levels of NSTR 9 products per scenario

NSTR	Description	3DCSM scores per scenario					Decentralization per scenario				
		Pr.	Sc. L	Sc. B.	Sc. H	Sc. X	Pr.	Sc. L	Sc. B.	Sc. H	Sc. X
9	**Vehicles, machinery and other manufactured goods**										
91	**Transportation equipment**										
910	Transport equipment, whether or not assembled parts thereof	39.6%	49.5%	63.1%	69.3%	100.0%	0.75%	2.35%	8.27%	13.38%	88.10%
92	**Agricultural tracts and machinery**										
920	Agricultural tracts and equipment, whether or not assembled parts thereof	50.0%	59.6%	73.0%	78.4%	100.0%	2.49%	6.16%	17.42%	25.21%	88.10%
93	**Electric and other machinery, apparatus**										
931	Electric machinery, apparatus, engines	22.9%	32.5%	45.9%	51.3%	100.0%	0.04%	0.27%	1.60%	2.85%	88.10%
939	Non-electric machinery, apparatus	6.3%	16.1%	29.8%	36.0%	100.0%	0.00%	0.01%	0.17%	0.46%	88.10%
94	**Manufactures of material**										
941	Finished structural parts of metal	-33.3%	-18.3%	-6.1%	-1.5%	100.0%	0.00%	0.00%	0.00%	0.00%	88.10%
949	Other manufactures of metal	-10.4%	1.5%	12.1%	15.2%	100.0%	0.00%	0.00%	0.00%	0.01%	88.10%
95	**Glass, glassware and ceramic products**										
951	Glass	-27.1%	-15.1%	-12.9%	-9.8%	100.0%	0.00%	0.00%	0.00%	0.00%	88.10%
952	Glassware, pottery, and other manufactures of minerals	12.5%	24.2%	26.1%	36.8%	100.0%	0.00%	0.06%	0.09%	0.51%	88.10%
96	**Leather, textiles and garments**										
961	Leather and furs	31.3%	34.9%	37.1%	40.2%	54.2%	0.22%	0.39%	0.54%	0.81%	3.76%
962	Textile yarn, fabrics, made-up articles and related products	31.3%	34.9%	37.1%	40.2%	54.2%	0.22%	0.39%	0.54%	0.81%	3.76%
963	Clothing and footwear	62.5%	62.8%	63.1%	63.8%	70.8%	7.85%	8.01%	8.23%	8.75%	14.94%
97	**Other finished and semi manufactured products**										
971	Finished and semi manufactured rubber products	22.9%	26.3%	28.2%	30.5%	100.0%	0.04%	0.09%	0.13%	0.20%	88.10%
972	Paper and cardboard	-22.9%	-11.2%	-9.3%	-7.0%	0.0%	0.00%	0.00%	0.00%	0.00%	0.00%
973	Paper and cardboard manufactures	-8.3%	3.4%	5.3%	7.6%	14.6%	0.00%	0.00%	0.00%	0.00%	0.00%
974	Paper matter	-16.7%	-5.0%	-3.1%	-0.7%	6.3%	0.00%	0.00%	0.00%	0.00%	0.00%
975	Furniture, new	62.5%	62.8%	63.1%	63.8%	100.0%	7.85%	8.01%	8.23%	8.75%	88.10%
976	Wood and cork manufactures, excluding furniture	-25.0%	-13.0%	-10.8%	-7.8%	6.3%	0.00%	0.00%	0.00%	0.00%	0.00%
979	Other manufactured articles	10.4%	19.3%	19.9%	21.4%	100.0%	0.00%	0.02%	0.02%	0.03%	88.10%
99	**Miscellaneous articles**										

991	Packing containers, used	-	-	-	-	-	-	-	-	-	-
992	Construction materials, used	-	-	-	-	-	-	-	-	-	-
993	Removal equipment	-	-	-	-	-	-	-	-	-	-
994	Pearls, precious stones, precious metals (gold), coins	56.3%	59.4%	60.9%	62.5%	100.0%	4.56%	6.03%	6.89%	7.85%	88.10%
999	Other manufactured goods	27.1%	35.7%	36.0%	36.8%	100.0%	0.11%	0.44%	0.46%	0.51%	88.10%

Figure P-2 The impact of decentralized production of NSTR 9 ono supplying NSTR group products per scenario

NSTR	Reduction in transported TEUs					Supplying NSTR group	Increase in transported TEUs				
	Pr.	Sc. L	Sc. B.	Sc. H	Sc. X		Pr.	Sc. L	Sc. B.	Sc. H	Sc. X
9											
91											
910	-2.353%	-8.272%	-13.381%	-88.100%	-2.353%	**NSTR 5**	+0.65%	+1.72%	+2.50%	+10.80%	+0.65%
92											
920	-6.157%	-17.419%	-25.213%	-88.100%	-6.157%	**NSTR 5**	+0.11%	+0.26%	+0.34%	+0.90%	+0.11%
93											
931	-0.273%	-1.602%	-2.849%	-88.100%	-0.273%	**NSTR 5**	+0.14%	+0.55%	+0.86%	+12.39%	+0.14%
939	-0.007%	-0.174%	-0.459%	-88.100%	-0.007%	**NSTR 5**	+0.01%	+0.10%	+0.21%	+12.53%	+0.01%
94											
941	0.000%	0.000%	0.000%	-88.100%	0.000%	**NSTR 5**	+0.01%	+0.00%	+0.00%	+9.85%	+0.01%
949	0.000%	-0.002%	-0.005%	-88.100%	0.000%	**NSTR 5**	+0.00%	+0.00%	+0.00%	+4.78%	+0.00%
95											
951	0.000%	0.000%	0.000%	-88.100%	0.000%	**NSTR 6**	+0.00%	+0.00%	+0.00%	+0.66%	+0.00%
952	-0.060%	-0.088%	-0.510%	-88.100%	-0.060%	**NSTR 6**	+0.01%	+0.01%	+0.04%	+2.01%	+0.01%
96											
961	-0.390%	-0.536%	-0.806%	-3.757%	-0.390%	**NSTR 0**	+0.01%	+0.01%	+0.01%	+0.05%	+0.01%
962	-0.390%	-0.536%	-0.806%	-3.757%	-0.390%	**NSTR 0**	+0.07%	+0.09%	+0.13%	+0.43%	+0.07%
963	-8.008%	-8.230%	-8.746%	-14.939%	-8.008%	**NSTR 0**	+0.91%	+0.93%	+0.98%	+1.48%	+0.91%
97											
971	-0.091%	-0.130%	-0.196%	-88.100%	-0.091%	**NSTR 0**	+0.01%	+0.01%	+0.02%	+2.31%	+0.01%
972	0.000%	0.000%	0.000%	0.000%	0.000%	**NSTR 8**	+0.00%	+0.00%	+0.00%	+0.00%	+0.00%
973	0.000%	0.000%	0.000%	-0.004%	0.000%	**NSTR 8**	+0.00%	+0.00%	+0.00%	+0.00%	+0.00%
974	0.000%	0.000%	0.000%	0.000%	0.000%	**NSTR 8**	+0.00%	+0.00%	+0.00%	+0.00%	+0.00%
975	-8.008%	-8.230%	-8.746%	-88.100%	-8.008%	**NSTR 0**	+0.70%	+0.71%	+0.75%	+4.51%	+0.70%

976	0.000%	0.000%	0.000%	0.000%	0.000%	**NSTR 0**	+0.00%	+0.00%	+0.00%	+0.00%	+0.00%
979	-0.018%	-0.022%	-0.032%	-88.100%	-0.018%	**NSTR 0 & 8**	+0.01%	+0.01%	+0.02%	+7.77%	+0.01%
99											
991						**NSTR 8**	-	-	-	-	-
992						**NSTR 5**	-	-	-	-	-
993						**NSTR 5**	-	-	-	-	-
994	-6.025%	-6.887%	-7.845%	-88.100%	-6.025%	**NSTR 5**	+0.00%	+0.00%	+0.00%	+0.00%	+0.00%
999	-0.438%	-0.459%	-0.510%	-88.100%	-0.438%	**NSTR 5 & 8**	+0.46%	+0.48%	+0.52%	+28.47%	+0.46%
Total	-1.553%	-2.354%	-3.131%	-62.072%	-1.553%						

Table P-1 Total increase per NSTR raw material group

	Sc. L	Sc. B.	Sc. H	Sc. X
NSTR0	1.5%	1.6%	1.7%	18.3%
NSTR5	0.6%	2.1%	3.5%	87.8%
NSTR6	0.0%	0.0%	0.0%	4.2%
NSTR8	0.0%	0.0%	0.1%	9.1%

Appendix Q – World Container Model results

Q.1 Throughput

Table Q-1 TEU throughput total

Scenario	TEUs throughput	Change from 2006	Change from 2035 base
2006	376 871 372	0.0%	-72.918%
2035 base	1 391 606 286	269.3%	0.000%
Sc. L	1 387 477 652	268.2%	-0.297%
Sc. M	1 385 462 647	267.6%	-0.441%
Sc. Mi	1 384 499 267	267.4%	-0.511%
Sc. H	1 383 491 072	267.1%	-0.583%
Sc. X	1 248 346 833	231.2%	-10.295%

Table Q-2 Throughput of top 10 ports

	2006	2035	Sc. L	Sc. M	Sc. Mi	Sc. H	Sc. X
SINGAPORE	0%	357.5%	356.5%	355.9%	355.7%	355.3%	319.7%
HONG KONG	0%	359.1%	357.9%	357.4%	357.1%	356.8%	318.3%
YANTIAN	0%	370.7%	369.3%	368.6%	368.4%	368.0%	322.1%
KAOHSIUNG	0%	277.4%	275.9%	275.2%	274.8%	274.6%	228.0%
CHIWAN	0%	383.9%	382.7%	382.3%	382.1%	381.8%	346.5%
LONG BEACH	0%	251.1%	249.2%	248.2%	247.5%	247.2%	176.9%
ROTTERDAM	0%	184.6%	183.4%	182.8%	182.4%	182.2%	142.2%
PUSAN	0%	374.4%	372.8%	372.4%	372.1%	372.0%	341.7%
ANTWERP	0%	168.4%	167.2%	166.7%	166.4%	166.1%	127.9%
TANJUNG PELEPAS	0%	396.7%	395.2%	394.5%	394.2%	393.9%	351.2%
SINGAPORE		0%	-0.224%	-0.347%	-0.399%	-0.469%	-8.254%
HONG KONG		0%	-0.265%	-0.380%	-0.453%	-0.500%	-8.884%
YANTIAN		0%	-0.303%	-0.444%	-0.482%	-0.569%	-10.320%
KAOHSIUNG		0%	-0.408%	-0.584%	-0.697%	-0.761%	-13.107%

CHIWAN	0%	-0.252%	-0.342%	-0.367%	-0.444%	-7.739%
LONG BEACH	0%	-0.522%	-0.813%	-1.005%	-1.095%	-21.122%
ROTTERDAM	0%	-0.437%	-0.642%	-0.769%	-0.849%	-14.918%
PUSAN	0%	-0.342%	-0.419%	-0.494%	-0.506%	-6.887%
ANTWERP	0%	-0.427%	-0.642%	-0.733%	-0.835%	-15.068%
TANJUNG PELEPAS	0%	-0.297%	-0.436%	-0.509%	-0.570%	-9.152%

Table Q-3 Top 20 in terms of throughput

2006		2035 base		Sc. L		Sc. M		Sc. Mi		Sc. H		Sc. X	
SINGAPORE	22 985 084	SINGAPORE	22 985 084	SINGAPORE	104 918 918	SINGAPORE	104 789 760	SINGAPORE	104 735 009	SINGAPORE	104 661 827	SINGAPORE	96 475 034.06
HONG KONG	17 218 319	HONG KONG	17 218 319	HONG KONG	78 846 526	HONG KONG	78 755 427	HONG KONG	78 698 131	HONG KONG	78 660 879	HONG KONG	72 032 326.51
YANTIAN	16 561 411	YANTIAN	16 561 411	YANTIAN	77 719 074	YANTIAN	77 608 777	YANTIAN	77 579 356	YANTIAN	77 511 704	YANTIAN	69 910 370.14
KAOHSIUNG	12 028 663	CHIWAN	10 963 908	CHIWAN	52 923 082	CHIWAN	52 875 592	CHIWAN	52 862 384	CHIWAN	52 821 400	CHIWAN	48 950 975.82
CHIWAN	10 963 908	KAOHSIUNG	12 028 663	KAOHSIUNG	45 214 702	KAOHSIUNG	45 134 413	KAOHSIUNG	45 083 449	KAOHSIUNG	45 054 073	PUSAN	40 495 585.31
LONG BEACH	10 045 447	PUSAN	9 167 608	PUSAN	43 342 369	PUSAN	43 308 760	PUSAN	43 276 096	PUSAN	43 270 791	KAOHSIUNG	39 449 220.03
ROTTERDAM	9 895 408	TANJUNG PELEPAS	7 488 254	TANJUNG PELEPAS	37 083 095	TANJUNG PELEPAS	37 031 279	TANJUNG PELEPAS	37 004 311	TANJUNG PELEPAS	36 981 413	TANJUNG PELEPAS	33 789 459.44
PUSAN	9 167 608	LONG BEACH	10 045 447	LONG BEACH	35 082 463	LONG BEACH	34 979 651	LONG BEACH	34 911 822	LONG BEACH	34 880 232	NANSHA	28 052 503.68
ANTWERP	7 691 304	NANSHA	29 582 279	NANSHA	29 532 479	NANSHA	29 514 932	NANSHA	29 495 574	NANSHA	29 492 502	LONG BEACH	27 817 353.35
TANJUNG PELEPAS	7 488 254	ROTTERDAM	9 895 408	ROTTERDAM	28 042 227	ROTTERDAM	27 984 570	ROTTERDAM	27 948 704	ROTTERDAM	27 926 123	SURABAYA	24 374 042.25
HAMBURG	6 297 092	SURABAYA	27 013 198	SURABAYA	26 939 406	SURABAYA	26 897 949	SURABAYA	26 887 544	SURABAYA	26 858 452	ROTTERDAM	23 963 674.94
DUBAI	6 191 435	XIAMEN	24 748 494	XIAMEN	24 700 283	XIAMEN	24 682 978	XIAMEN	24 667 479	XIAMEN	24 658 293	XIAMEN	23 276 519.79

KOBE	6 149 601	LAEM CHABANG	23 751 906	LAEM CHABANG	23 679 670	LAEM CHABANG	23 651 938	LAEM CHABANG	23 637 061	LAEM CHABANG	23 622 536	LAEM CHABANG	21 656 577.23
NANSHA	6 035 147	SHANGHAI	20 810 918	SHANGHAI	20 745 102	SHANGHAI	20 707 840	SHANGHAI	20 701 038	SHANGHAI	20 684 016	DUBAI	19 247 291.08
OSAKA	5 347 659	ANTWERP	7 691 304	ANTWERP	20 553 909	ANTWERP	20 509 492	ANTWERP	20 490 718	ANTWERP	20 469 614	SHANGHAI	18 737 428.89
SURABAYA	5 248 196	DUBAI	20 413 464	DUBAI	20 396 818	DUBAI	20 373 240	DUBAI	20 360 812	DUBAI	20 352 345	SHEKOU	18 212 958.05
XIAMEN	4 915 881	SHEKOU	19 961 384	SHEKOU	19 908 297	SHEKOU	19 880 038	SHEKOU	19 870 911	SHEKOU	19 857 586	ANTWERP	17 531 774.34
VANCOUVER	4 281 662	KOBE	19 638 483	KOBE	19 550 045	KOBE	19 519 884	KOBE	19 499 552	KOBE	19 489 383	KOBE	17 229 134.95
SHANGHAI	4 263 898	HAMBURG	17 287 925	HAMBURG	17 173 122	HAMBURG	17 120 349	HAMBURG	17 094 273	HAMBURG	17 068 450	BRISBANE	16 244 342.72
BRISBANE	4 244 537	BRISBANE	16 829 956	BRISBANE	16 817 984	BRISBANE	16 808 439	BRISBANE	16 803 084	BRISBANE	16 798 169	CHENNAI	15 786 084.05

Q.2 Container flow

Table Q-4 Container flow in TEUs

Scenario	Container flow (TEUs)	Change from 2006	Change from 2035 base
2006	154 999 227	0.0%	-73.509%
2035 base	585 092 652	277.5%	0.000%
Sc. L	583 345 501	276.4%	-0.299%
Sc. M	582 504 977	275.8%	-0.442%
Sc. Mi	582 068 383	275.5%	-0.517%
Sc. H	581 679 769	275.3%	-0.583%
Sc. X	525 334 570	238.9%	-10.213%

Table Q-5 Largest container flow compared to 2006

Port pair	Sc. L	Sc. M	Sc. Mi	Sc. H	Sc. X
BANDAR ABBAS-PORT KLANG	538.539%	538.695%	539.147%	539.038%	616.311%
NANSHA-YANTIAN	394.765%	394.667%	394.453%	394.249%	379.068%
YANTIAN-HONG KONG	393.270%	393.175%	392.965%	392.760%	377.796%
YANTIAN-CHIWAN	391.729%	391.633%	392.348%	392.143%	376.322%
CHIWAN-YANTIAN	395.048%	394.945%	394.729%	394.522%	378.997%
XIAMEN-YANTIAN	394.358%	394.268%	394.057%	393.857%	379.186%
SHEKOU-YANTIAN	394.272%	394.182%	393.970%	393.770%	379.062%
JEDDAH-SINGAPORE	461.352%	461.542%	462.270%	461.840%	529.465%
NANSHA-HONG KONG	393.088%	392.854%	391.825%	392.592%	377.854%
HONG KONG-YANTIAN	395.204%	395.098%	394.881%	394.673%	378.970%
ROTTERDAM-IMMINGHAM	-0.563%	-0.813%	-1.053%	-1.069%	-19.046%

Table Q-6 Largest container flow compared to 2035

Port pair	2035 base	Sc. L	Sc. M	Sc. Mi	Sc. H	Sc. X

BANDAR ABBAS-PORT KLANG	0%	0.646%	0.671%	0.742%	0.725%	12.905%
NANSHA-YANTIAN	0%	-0.090%	-0.110%	-0.153%	-0.195%	-3.260%
YANTIAN-HONG KONG	0%	-0.090%	-0.109%	-0.152%	-0.193%	-3.224%
YANTIAN-CHIWAN	0%	-0.090%	-0.110%	0.036%	-0.006%	-3.221%
CHIWAN-YANTIAN	0%	-0.093%	-0.114%	-0.158%	-0.199%	-3.333%
XIAMEN-YANTIAN	0%	-0.086%	-0.105%	-0.147%	-0.188%	-3.153%
SHEKOU-YANTIAN	0%	-0.087%	-0.105%	-0.148%	-0.188%	-3.161%
JEDDAH-SINGAPORE	0%	0.583%	0.617%	0.748%	0.671%	12.788%
NANSHA-HONG KONG	0%	-0.090%	-0.137%	-0.346%	-0.190%	-3.176%
HONG KONG-YANTIAN	0%	-0.095%	-0.116%	-0.160%	-0.202%	-3.370%
ROTTERDAM-IMMINGHAM	0%	-0.563%	-0.813%	-1.053%	-1.069%	-19.046%

Table Q-7 Top 10 container flows

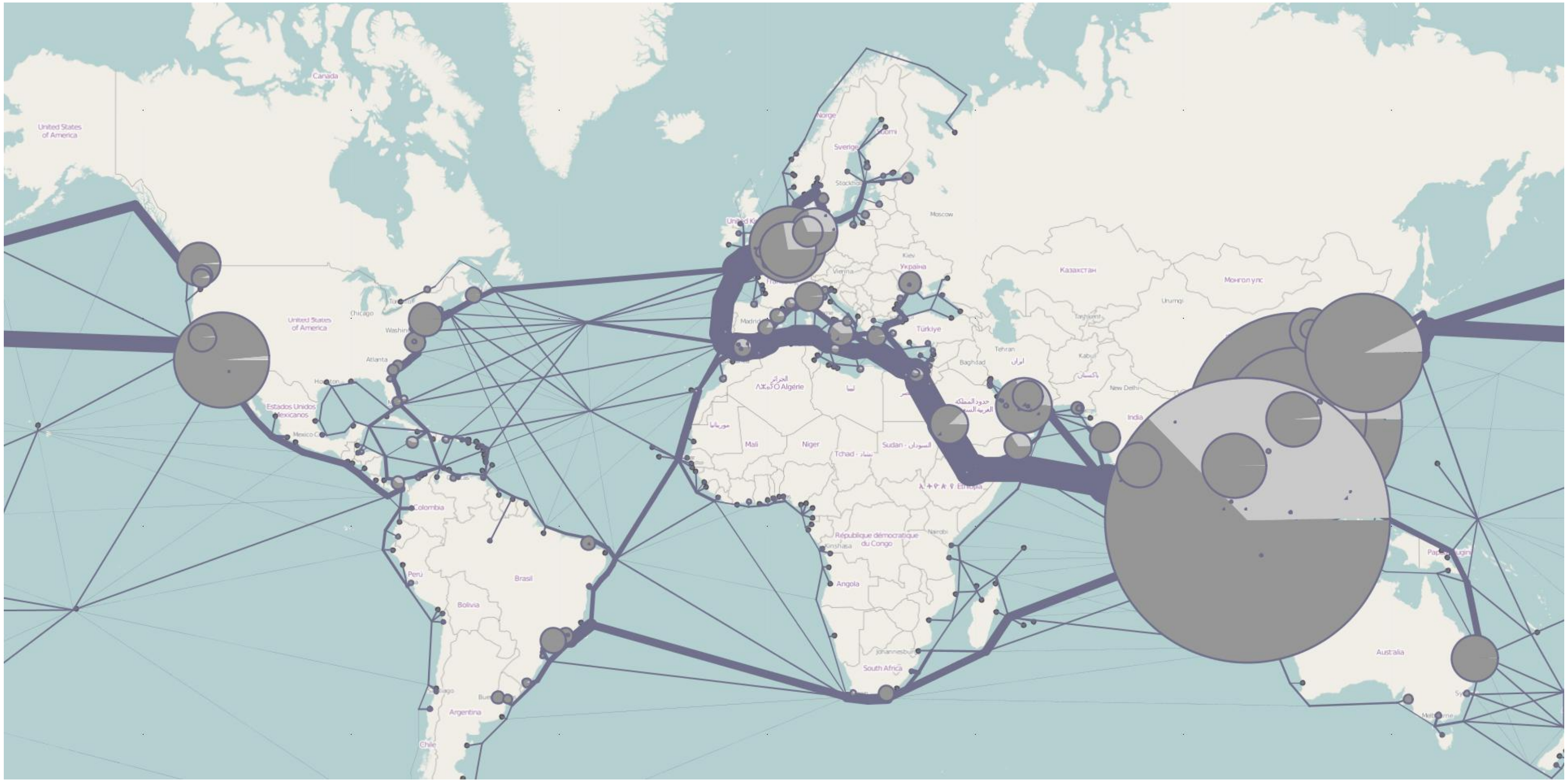
2006		2035 base		Sc. L		Sc. M		Sc. Mi		Sc. H		Sc. X	
ROTTERDAM-IMMINGHAM	1 237 634	BANDAR ABBAS-PORT KLANG	5 491 009	BANDAR ABBAS-PORT KLANG	5 526 500	BANDAR ABBAS-PORT KLANG	552 784 6	BANDAR ABBAS-PORT KLANG	553 176 3	BANDAR ABBAS-PORT KLANG	553 081 8	BANDAR ABBAS-PORT KLANG	619 960 8
BRISBANE-OSAKA	1 138 266	NANSHA-YANTIAN	5 357 690	NANSHA-YANTIAN	5 352 843	NANSHA-YANTIAN	535 178 1	NANSHA-YANTIAN	534 946 7	NANSHA-YANTIAN	534 726 1	NANSHA-YANTIAN	518 301 7
NANSHA-YANTIAN	1 081 896	YANTIAN-HONG KONG	5 257 441	YANTIAN-HONG KONG	5 252 707	YANTIAN-HONG KONG	525 168 9	YANTIAN-HONG KONG	524 945 4	YANTIAN-HONG KONG	524 727 7	YANTIAN-HONG KONG	508 792 3
YANTIAN-HONG KONG	1 064 874	YANTIAN-CHIWAN	5 206 256	YANTIAN-CHIWAN	5 201 560	YANTIAN-CHIWAN	520 055 0	YANTIAN-CHIWAN	520 811 4	YANTIAN-CHIWAN	520 594 4	YANTIAN-CHIWAN	503 858 7
YANTIAN-CHIWAN	1 057 811	CHIWAN-YANTIAN	4 810 669	CHIWAN-YANTIAN	4 806 185	CHIWAN-YANTIAN	480 517 7	CHIWAN-YANTIAN	480 308 5	CHIWAN-YANTIAN	480 107 8	CHIWAN-YANTIAN	465 034 7

CHIWAN-YANTIAN	970 852	XIAMEN-YANTIAN	4 698 933	XIAMEN-YANTIAN	4 694 872	XIAMEN-YANTIAN	469 401 9	XIAMEN-YANTIAN	469 200 9	XIAMEN-YANTIAN	469 011 4	XIAMEN-YANTIAN	455 078 1
XIAMEN-YANTIAN	949 691	SHEKOU-YANTIAN	4 404 395	SHEKOU-YANTIAN	4 400 578	SHEKOU-YANTIAN	439 977 4	SHEKOU-YANTIAN	439 788 7	SHEKOU-YANTIAN	439 610 9	SHEKOU-YANTIAN	426 516 5
SHEKOU-YANTIAN	890 315	JEDDAH-SINGAPORE	4 124 326	JEDDAH-SINGAPORE	4 148 375	JEDDAH-SINGAPORE	414 978 0	JEDDAH-SINGAPORE	415 516 1	JEDDAH-SINGAPORE	415 198 2	JEDDAH-SINGAPORE	465 172 9
BANDAR ABBAS-PORT KLANG	865 491	NANSHA-HONG KONG	4 093 067	NANSHA-HONG KONG	4 089 399	NANSHA-HONG KONG	408 745 6	NANSHA-HONG KONG	407 892 3	NANSHA-HONG KONG	408 528 5	NANSHA-HONG KONG	396 305 8
NANSHA-HONG KONG	829 345	HONG KONG-YANTIAN	4 073 500	HONG KONG-YANTIAN	4 069 646	HONG KONG-YANTIAN	406 876 9	HONG KONG-YANTIAN	406 699 2	HONG KONG-YANTIAN	406 528 0	HONG KONG-YANTIAN	393 623 3
		ROTTERDAM-IMMINGHAM	3 138 141	ROTTERDAM-IMMINGHAM	31204 81.829	ROTTERDAM-IMMINGHAM	311 261 9	ROTTERDAM-IMMINGHAM	310 508 2	ROTTERDAM-IMMINGHAM	310 459 9	ROTTERDAM-IMMINGHAM	254 045 2

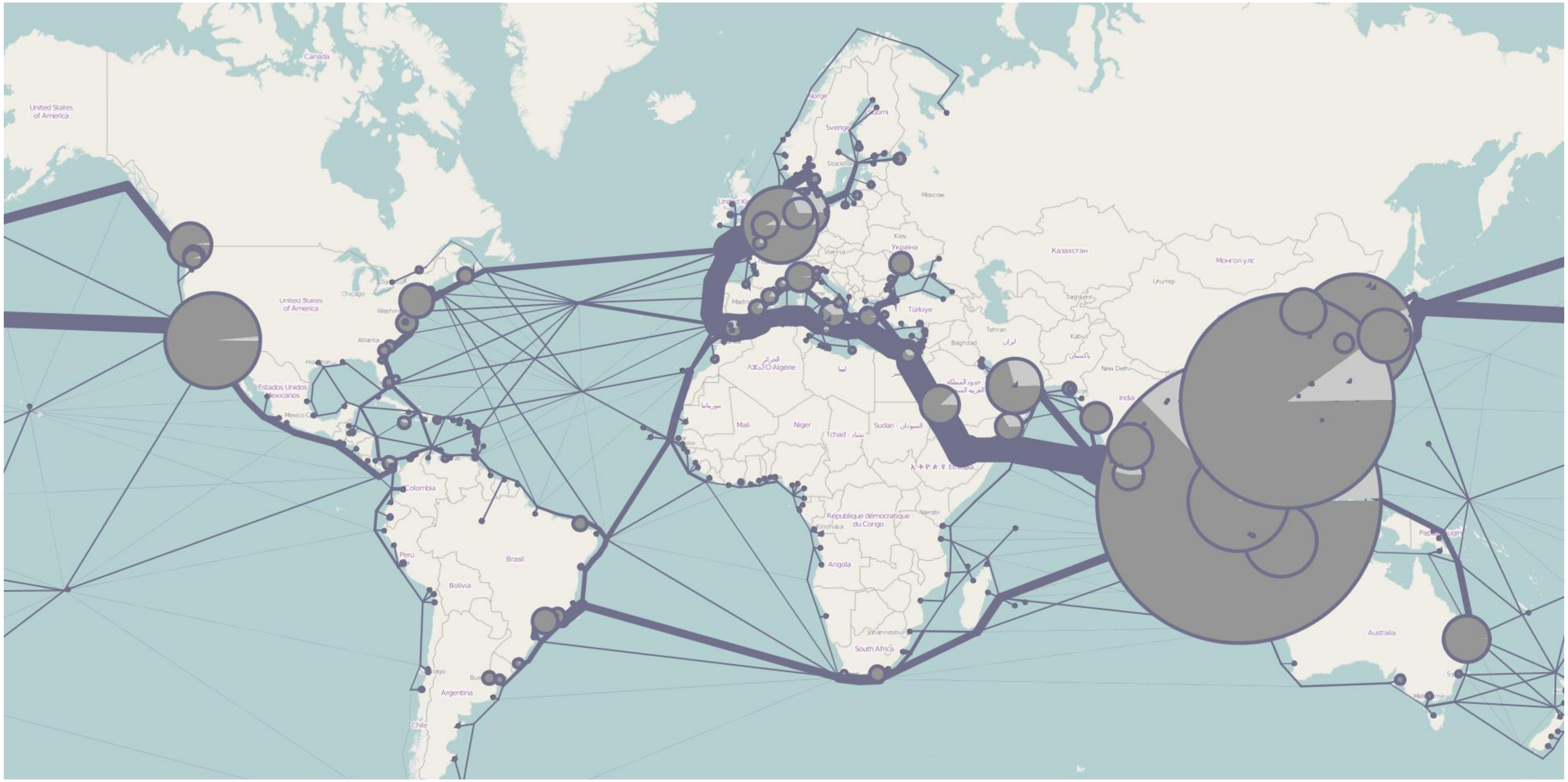
Appendix R - WCM generated images

R.1 2006

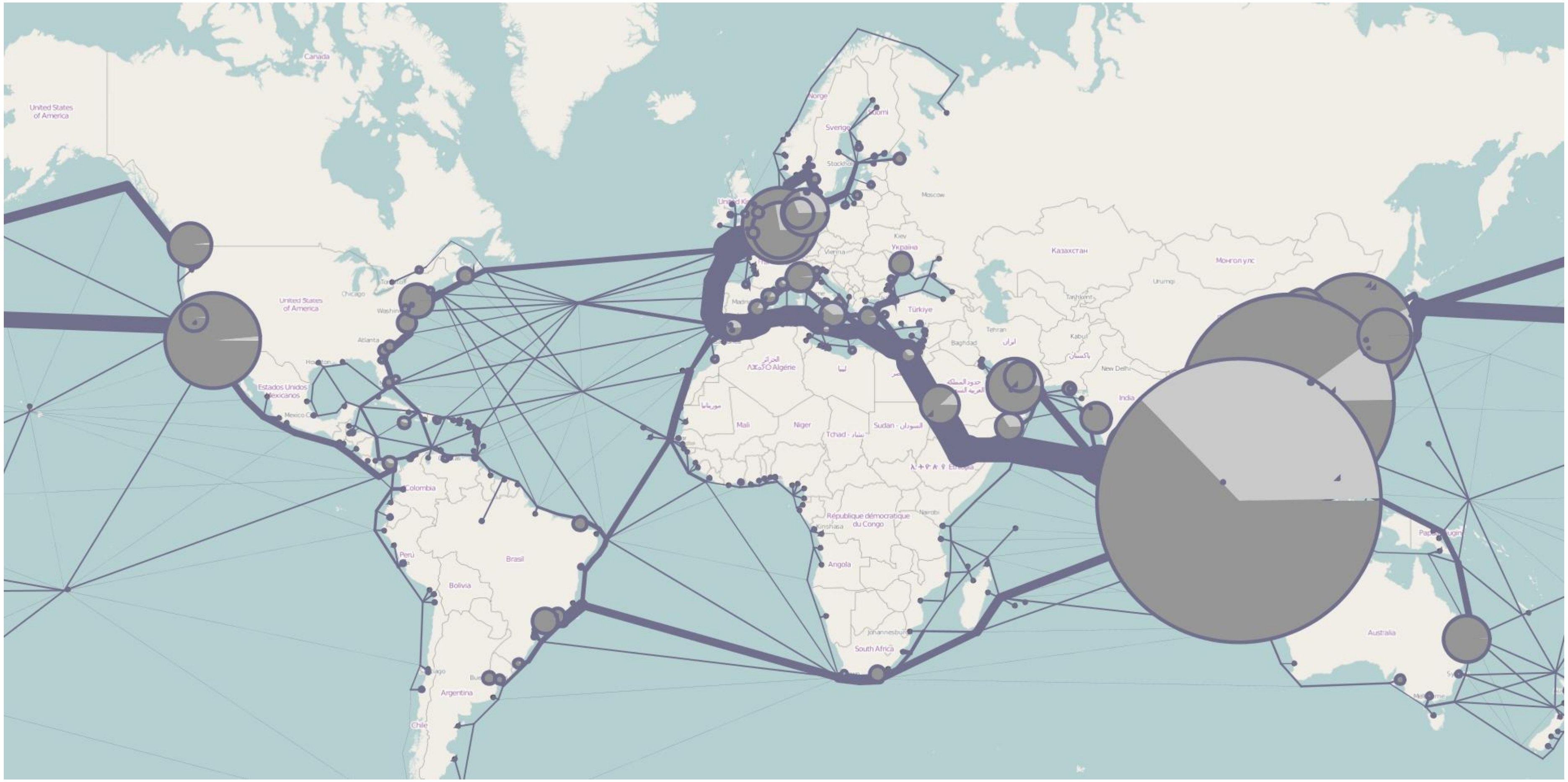
R.2 2035 Base



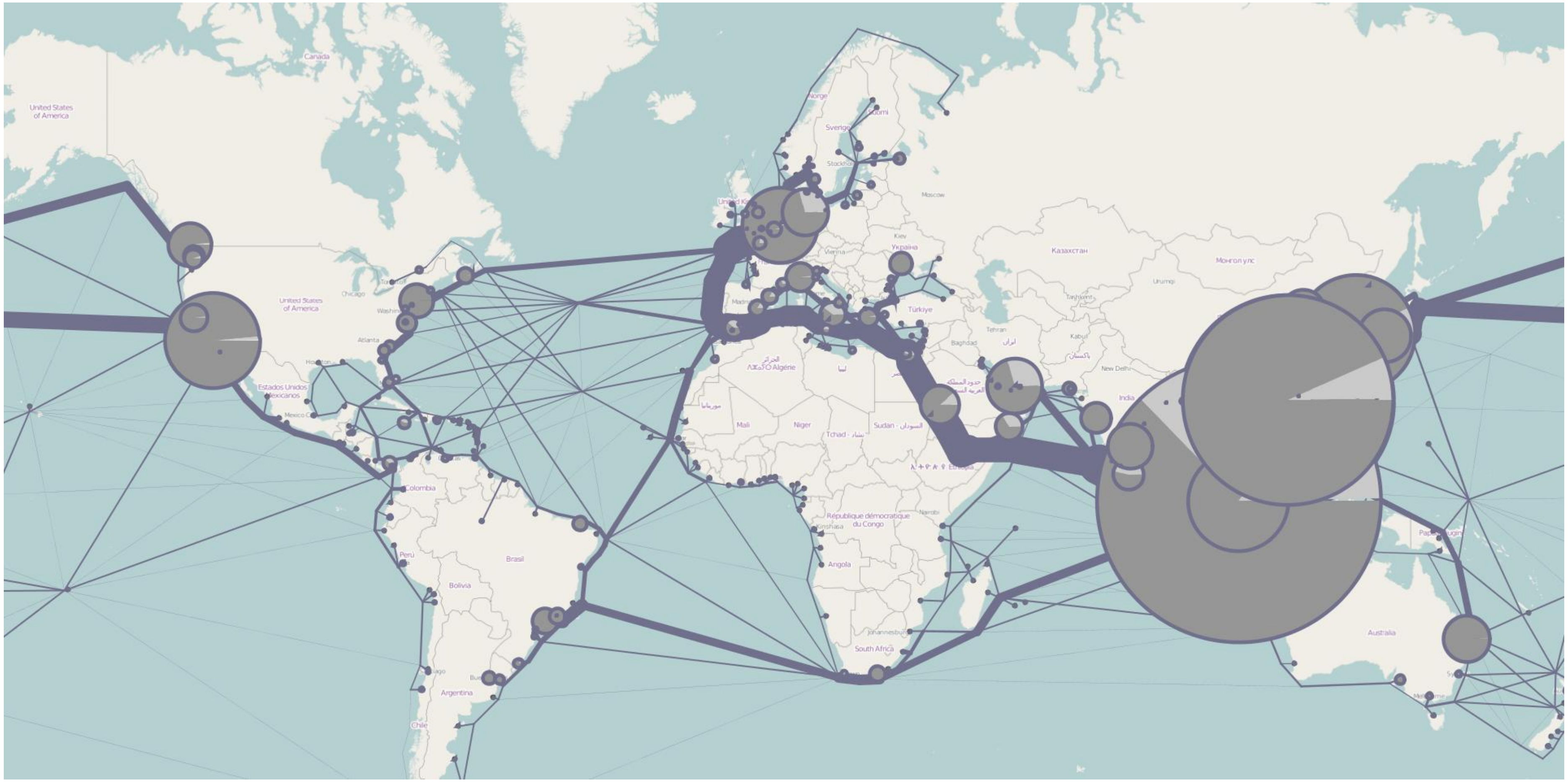
R.3 Scenario L



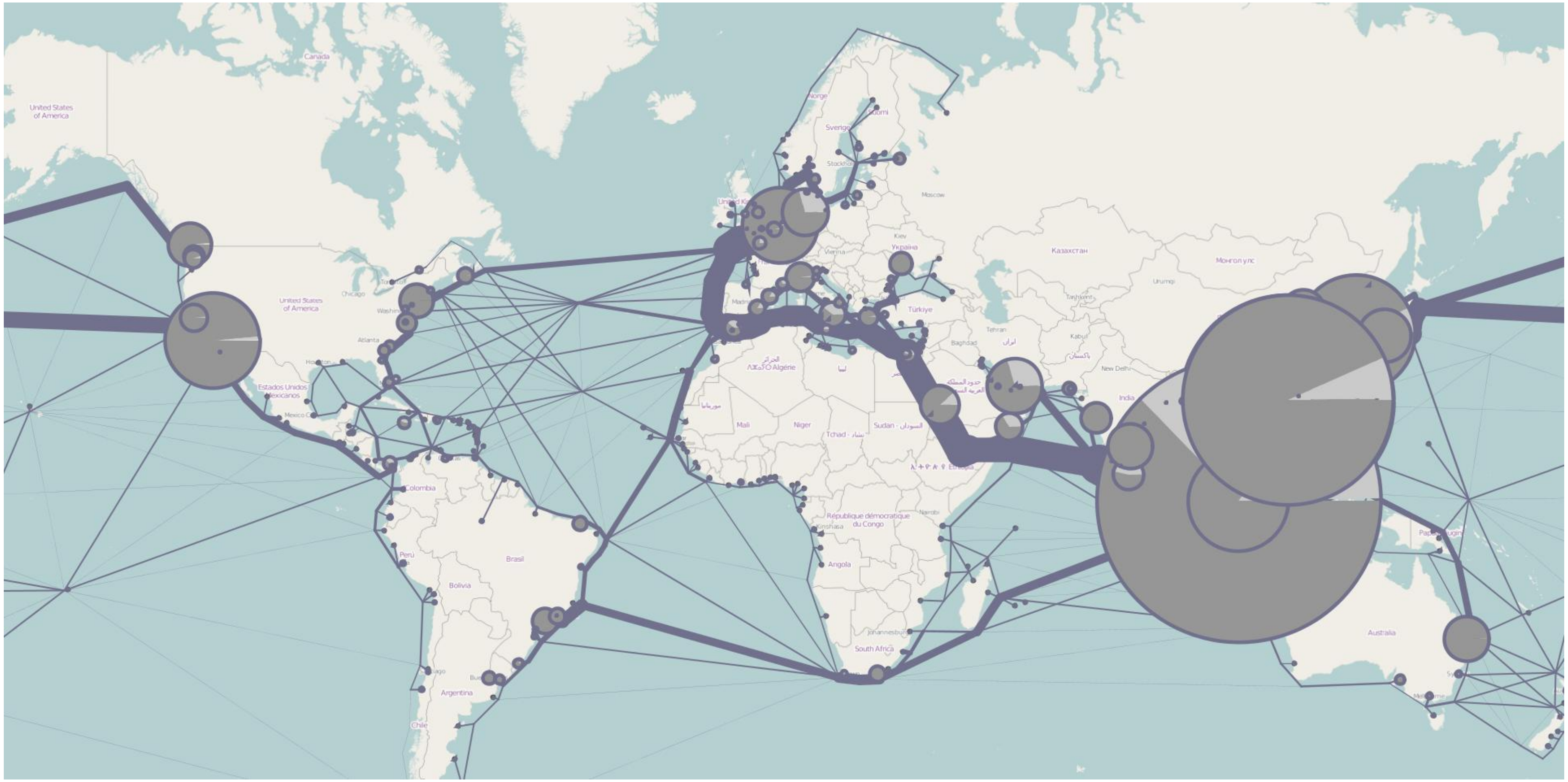
R.4 Scenario M



R.5 Scenario Mi



R.6 Scenario H



R.7 Scenario X