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The development of 3D printing
Guiding visions towards a desirable future

Achtergrond document

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The development of 3D printing

De afgelopen paar jaar is het 3D printen steeds populairder geworden. Met deze relatief nieuwe techniek kunnen producten laagje voor laagje opgebouwd worden, in plaats van het verwijderen van materiaal van groter stuk. Doordat er door de techniek grote ontwerpvrijheid ontstond, kwamen lang gekoesterde wensen zoals het direct printen van prototypes en het printen van medische protheses binnen bereik.

Aan innovaties kleven echter soms ook nadelen. Het is van belang voor beleidsmakers en voor hen die verantwoordelijk zijn voor product- en voedselveiligheid om hier tijdig van op de hoogte te zijn. Dat is overigens ook in het belang van de ontwikkelaars, omdat deze zaken een succesvolle uitrol van de techniek in de weg kunnen staan.

Een goede manier om een idee te krijgen van de richting waarin een techniek zich ontwikkeld is het in kaart brengen van de visies op de toekomst van de techniek van ontwikkelaars en vroege toepassers. Hun visie is vaak een goede voorspeller en drijfveer van de ontwikkelingsrichting. In dit onderzoek zijn de visies op de ontwikkeling van industriële 3D printen, consumenten 3D printen, healthcare printen en voedsel printen in kaart gebracht.

Uit het onderzoek blijkt dat in alle vier de domeinen de verwachtingen hooggespannen zijn. De verwachting is dat rond 2060 zowel industriële als consumententoepassingen heel gewoon zijn. Van het 3D printen van voedsel verwacht men bijvoorbeeld dat dit thuis kan gebeuren, waarbij rekening gehouden wordt met individuele voorkeuren. Ook in het medische domein voorziet men vele toepassingen. Een aspect van de technologie dat aanzienlijke aandacht verdient, is de vooralsnog beperkte kennis over het effect van de technologie op productveiligheid.

Kernwoorden: Constructive Technology Assessment, Vision Assessment, 3D printen, Healthcare printen, Voedsel printen

Synopsis

The development of 3D printing

Over the past few years, 3D printing has become increasingly popular. This relatively new technique allows products to be built up layer by layer, in place of the removal of material from a larger piece. Because the technique enables great freedom in design, long cherished wishes such as direct printing of prototypes and printing of medical prostheses became within reach.

Innovations, however, sometimes have disadvantages. It is important for policy makers and for those responsible for product and food safety to be timely informed here. That is also in the interests of the developers, because these issues can compromise a successful application of the technology.

A good way to get an idea of the direction in which a technique develops, is the assessment of the visions of the future of technology held by developers and early adopters. Their vision is often a good predictor and driver of the direction of a technological development. In this study the visions on the development of industrial 3D printing, 3D printing consumer, healthcare and food printing have been assessed.

The study shows that in all four domains, the expectations are high. It is expected that around 2060 both industrial and consumer applications are very common. For the 3D printing of food, for example, it is expected that this can be done at home, taking into account individual preferences. Moreover, it is expected that in the medical domain many applications of 3D printing will be used. An aspect of the technology that deserves attention is the still limited knowledge about the effects of 3D printing om product safety.

Keywords: Constructive Technology Assessment, Vision Assessment, 3D printing, Healthcare printing, Food printing

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Summary

In recent years, 3D printing gained increasing popularity in society. This relatively new technology build products layer-by-layer, additively, rather than by subtracting material from a larger piece, such as the conventional ways like forming, molding and machining. Due to this technology, long wished aims such as freedom of design suddenly come into reach. Since the purchase of a 3D-printer and its materials became cheaper, it triggered professional and public use. Designers print jewels like bracelets and necklaces, architects print prototypes of their designs, in healthcare medical devices and prosthetics could be customized and chefs experiment with 3D print technologies to print food. It is the wide range of applications and high expectations that are probably the most striking aspect of 3D-printing.

Notwithstanding the innovative possibilities of 3D printing, some concerns raised among policymakers and regulatory regimes, who are responsible for product safety and prevention of health risks. Currently, it is unknown which applications might originate from developments in 3D printing. Therefore, potential impacts (positive and negative) that these technologies could have on the aspects of sustainability/environment, society and safety are uncertain. Without proper attention, negative impacts and barriers can compromise the successful application of 3D printing technologies in society. To identify potential impacts of emerging technologies and to orient on future actions, visions about the desirable future of a technology are required. It is assumed that the most explicit visions about the future of a technology exist among scientists and technology developers and users. This group of people has desires and ideals that guide technology development and triggers the actions to develop new products. Therefore, these visions are called guiding visions. To identify these potential impacts and to initiate discussion about them, guiding visions have been inventorized. Consequently, the research question of this research project is: What are the guiding visions concerning 3D printing applications and their impact on sustainability, safety and society, held by the 3D printing developers and users?

To identify the guiding visions, a Vision Assessment that consisted of a desk study and interviews was conducted. The aim of the desk study was to provide an overview of the current 3D printing technologies, an identification of relevant 3D printing domains and an overview of the developments per 3D print domain. This last insight was needed as it formed the baseline of understanding and questioning the participants in our qualitative study. The qualitative study consisted of nineteen semi-structured interviews. The participants covered four different application domains of 3D printing to represent most of the developments of 3D printing, namely: industrial printing, consumer printing, food printing and healthcare printing. The group of participants consisted of printer developers, printer users and scientists who conduct research on new print material or other developments.

In analyzing the guiding visions, the following four concepts were distinguished: current state of knowledge, purposes to be fulfilled,

interpretation of relevant contextual aspects and normative premises of desired final state. Based on these concepts, the data was categorized. Relevant sentences of the transcripts were labelled and resulted eventually in the following categories: current state, developments, future use, impact and conditions.

The results provide insight into the desires and expectations of technology developers and users concerning the future development of 3D printing and applications hereof. The developers and users envisioned 14 aspects of guiding visions which can be divided in the four fields of applications: industry, consumer, food and healthcare. First, the results show that in all application domains 3D printing is in its infancy. Consumer printing is currently a hype and the applications are not that divers. Also food printing is in its infancy, this application domain is in an experimental phase. In healthcare there are already some applications, such as customized prosthetics or customized medical instruments, but the use of these techniques is not common yet. Industrial printing is currently the most mature application domain. Some companies already work with industrial printers, although it turned out that the technology is not very reliable.

Because 3D printing is a relatively young technology many technological developments take place in all domains to improve the technology and software to make it more reliable and easy to use. It is desired to expand the pallet of materials in order to broaden the usability of 3D printing. Furthermore, there is a great desire to develop printers that could print with different types of material and full color. In this way products could be made that consist of different materials instead of just one material type. In the healthcare domain researchers focus on the development of living tissues, which could be used for different purposes, like replacement of damaged tissue in the human body.

Provided that the 3D print technology becomes mature and reliable, the expectations about the future use of 3D printing by the time of 2060 are high. In the industrial domain it is envisioned that the 3D printer becomes a common manufacturing technique that will still print prototypes but also high quality end products. These printers will print multimaterial and the manufacturing process becomes on demand and flexible. By the time of 2060 it is envisioned that consumer printers become a tool to manufacture at home or locally at a copy shop. Also for food printing it is envisioned that consumers could print food by the time of 2060. Additionally, this food will be personalized. In healthcare 3D printing will also be a common used technology that will be used for many applications: surgery planning, customized medical instruments, customized (hybrid) instruments and tissue engineering or regenerative medicines.

These visions might have impact on the environment, and some on safety and society. In general, 3D printing is seen as a sustainable technology which has a positive impact on the environment. Less material is wasted and due to the possibility of on demand production, fewer inventories are necessary and less transportation is needed. Furthermore, impact is envisioned on society. The society might no longer be dependent on the industry, because fabrication of own designs becomes more accessible and products become more adapted to the individual, because consumers will be able to adapt designs to their wishes. This study also found that the 3D print developments might have some safety effects. For example, there are some concerns about the unknown impact of 3D printing process on the quality of the products. It is unknown if the properties of material change during the manufacturing process and therefore the quality of the products could not always be guaranteed.

The findings of this research illustrate that the theory of Vision Assessment is an appropriate tool to make implicit guiding visions explicit. Besides the visions, this research identified concerns that need to be overcome and potential implications of 3D printing. Between de results was many consensus, though, the opinions of industrial experts and consumer experts about the extent of the use of consumer printers differed. Probably, because the consumer domain is at the top of the hype which mostly is associated with high expectations, the industrial domain on the other hand is already over the hype and therefore their opinions might be more adapted and realistic. Overall, it could be concluded that 3D printing is not a hype, which will pass by, but there is a great future on the horizon. Moreover, this study illustrates which aspects need further exploration and which of them need attention in order to develop 3D printing in desirable directions.

1 Introduction

In recent years, 3D printing gained increasing popularity in society. 3D printing belongs to a class of technologies known as rapid prototyping manufacturing (RPM) or additive manufacturing (AM). These technologies build products layer-by-layer, additively, rather than by subtracting material from a larger piece, such as the conventional ways like forming, molding and machining (Campbell et al., 2011). Through this new technology it is possible to build, without assembling, complex products that could never be made before. Due to 3D printing there is freedom of design (Campbell et al., 2011; McKinsey, 2012; Diginova, 2013).

Since the purchase of a 3D-printer and its materials became cheaper, it triggered professional and public use of the 3D printer (Campbell et al., 2011; Berman, 2012). Currently, consumer 3D printers are a hype (Gartner, 2013), which results in growing sales numbers of consumer 3D printers (Wohlers, 2014) . Meanwhile the industry already uses the technology for different type of applications like prototyping (Wohlers, 2014). Furthermore, 3D printing is used in the medical industry, which makes it possible to customize medical devices, like prostheses and implants. This particular application already occurs frequently based on scans of joints like hips, parts of the teeth but also for example hearing aids (Campbell et al., 2011; Schubert, Van Langeveld, & Donoso, 2014). Additionally, it is stated that 3D printing might replace animal testing, because research takes place to print organs and other living tissues (RIVM, 2013).

It is this wide range of applications and high expectations for the future that is probably the most striking aspect of 3D-printing. Although the technology is partly in its infancy, several studies stated that this upcoming technology could be seen as the 'third industrial revolution' (Berman, 2012; Birtchnell et al., 2013; Huang et al., 2013;), this is because of long wished aims such as freedom of design suddenly come into reach. Formerly, designers were limited by the different manufacturing technologies, now it is possible to print every shape. Furthermore, 3D printing could be revolutionary because this manufacturing technology becomes more accessible for consumers. In addition, the technique even promises solutions for difficult normative societal issues, like global warming, because due to 3D printing, digital product designs transfer around the world and companies are able to print the product at location (Campbell, 2012). Subsequently less transportation is needed which will lower the carbon footprint of production (Campbell, 2012).

Despite the enthusiasm about the new possibilities that 3D printing has to offer, some concerns raised among policymakers and regulatory regimes who are responsible for product safety and prevention of health risks. For example because Stephens (2013) stated that 3D printers have high emissions of ultrafine particles, which can be toxic for mammals. His results suggest that people should be cautious when using commercial 3D printers in unvented indoor environments.

Moreover, concerns raised about the quality of the printed objects. If the product has different characteristics than the designer intended due to the 3D print process, issues with the strength, durability and safety of the printed objects might rise. Imagine for instance an airplane or car mechanic that uses 3D printed spare parts with poor quality which could cause an early break down of the parts or machine, or imagine a printed toy which easily breaks down and could be swallowed by a child. These examples could bring people in dangerous situations. Furthermore, the possibility that consumers print their own products brings up questions about who is responsible for the printed objects and how could the product safety be guaranteed (Pierrakakis et al., 2014).

On account of the raised concerns The Dutch National Institute for Public Health and the Environment (RIVM) started a project to investigate which safety and health concerns need attention for further investigation and which concerns are current and which are coming. The RIVM is specialized in assessment of risks for health and environment. For example the institute conducts studies on health risks, like health effects due to air pollution. In regard to the emergence of 3D printing the RIVM is interested in the possible impact of 3D printing on sustainability/environment, society and safety. Nowadays, the institute increasingly recognizes it has to shift its risk assessment towards technology assessment. A switch from a perspective that looks predominantly at the possible negative consequences, towards a perspective that includes both possible negative and beneficial aspects of technology. Therefore, in this project the focus will be on both risks and benefits that may appear with the development of 3D printing for the environment, such as toxicity of 3D print materials as well as applications that increase the use of recycled material. Furthermore, societal benefits will be explored as well as societal concerns and ethical objections towards 3D printing developments. Safety refers to possible concerns about the safety of the 3D printing process and the impact of the process on product safety.

Currently, there is a lack of studies that identify the developments of 3D printing and the impact of these applications on the three aspects sustainability, safety and society. Therefore, in order to contribute to the project of the RIVM, the aim of this study is to gain more insight in the recent and future development of 3D printing and the impact of it on the three aspects: sustainability/environment, safety and society.

2 Theoretical background

In the next chapter the theories underlying this study are described. It explains how emerging technologies were managed in the past and what approaches to manage the development of emerging technologies are used in the present. This chapter ends with a conceptual model, which structures the theory into the relevant concepts for this study and leads to the formulation of the research questions.

2.1 Controlling emerging technologies

Controlling emerging technologies, like 3D printing, is a process that has changed over the past decades. In the past, the government was seen as a central actor. The government possessed most of the power and control and was at the top of the hierarchy (Renn, 2008). However, this perspective is not realistic in the case of emerging technologies and other policy domains in which there is interdependence between all of the policy actors. A better approach to control emerging technologies would be an approach where actors in a policy network cooperate towards jointly defined goals (Renn et al., 2011). Such an approach might avoid obstruction of processes by other policy actors. Moreover, the information that is required with actor involvement can be used to improve the quality of decision-making processes. Today, the term governance includes this involvement of actors and in which the government is no longer seen as the actor with most of the power and control. Renn (2011) describes governance as following: 'Governance embodies a non-hierarchically organized structure encompassing state and non-state actors bringing about collectively binding policies without superior authority'. This perspective thus draws attention to the diversity of actors, the diversity of their roles, their logic of action, the multiple relationships between them and all kind of dynamic networks emerging from these relationships (Renn et al., 2011). Involving relevant actors in an early phase of the innovation seems to be crucial for managing emerging technologies.

For emerging technologies however, the uncertainty of the direction of the development introduces an extra complexity in the so-called governance process. This is best explained by the Collingridge Dilemma, a well-known dilemma in the emerging technology field regarding the most appropriate moment when to start the management of emerging technologies (Collinridge, 1981). There are two problems. First, there is an information problem, the impact of the emerging technology cannot be easily predicted until the technology is fully developed and widely used. The second problem is a power problem: when the technology becomes fully developed, it is difficult to control or change it. This dilemma illustrates that when a government makes regulations to control the development at an early state, it may have no effect because the future might not turn out as expected or the regulations may constrain beneficial innovation. However, when the government waits until the technology fully developed it might be too late for proper management.

2.2 Managing emerging technologies by Technology Assessment

Technology assessment (TA) is a strategy that is developed as an approach to manage the development of technologies in such a way that the possibility of successful steering is still open. The philosophy behind TA according to Schot and Rip (1997) is: 'reduce the human costs of trial and error learning in society's handing of new technologies, and to do so by anticipating potential impacts and feeding these insights back into decision making, and into actors' strategies.' TA became a useful instrument for policy makers to make policies that lead to desirable development of technologies. Although the aim of TA was to provide early warning and provide insights on possible future impacts, it was argued by Rip et al. (1995) that TA primarily served as after-the-fact gatekeeper. It could not tackle down the problems that the Collingridge Dilemma describes, to both optimize benefits and minimize negative consequences of emerging technologies. In response, in the past decades many variations of TA arose, in order to realize a better societal embedding of science and technology. One of these approaches is Constructive Technology Assessment (CTA).

CTA opens up the innovation process in an early phase through dialogue between actors that are involved and affected by the technology and thereby aims to deal better with the impacts of science and technology development (Rip et al., 1995). In this approach, the focus is on actor involvement in an early phase. Actors interact with each other, make choices; some conduct research, while others develop products (Van Merkerk et al., 2008). Van Merkerk (2008) states that as a result of these activities, technology is developed in certain directions. Further, Roelofsen (2011) explains that interacting with actors have several beneficial impacts, such as: 'overcoming market failures, making use of the creative potential of users, enhancing the efficiency of the innovation process, and taking into account social acceptability of new technologies.' Therefore, by including actors during the development of a technology, it could provide more insight in the future development of the technology and possible impacts that are resulting therefrom.

2.3 Vision assessment

Vision assessment is a method that is used to investigate the desirable future from the perspective of different actors., which differs from scenarios because scenarios describe the possible future (Roelofsen et al., 2008). Visions about the future held by actors are necessary to learn about possible impacts, to get insights into the future orientation of the development and of the actions taken by the actors (Roelofsen et al., 2008). According to Grin and Grunwald (2000) visions can be described as mental images of a realistic future that are considered to be desirable and are also shared by a range of actors. As these visions guide the actions of actors they are also called guiding visions. Roelofsen (2008) questioned how the CTA process can be integrated with the approach of vision assessment. She describes that all actors, and especially technology developers, have a certain vision about what they want to achieve in the future or which end-users will use their product. Therefore, the visions from technology developers could be used as a start for CTA when emerging technologies are examined (Decker, 2000).

Roelofsen (2008) listed four reasons why vision assessment should be integrated in the CTA process:

1. Gathering guiding visions could give more insights in what technology developers think is a desirable future and their perspective on how their technology will be used.
2. Guiding visions are needed to determine which actors are relevant and identify areas of application.
3. The visions are needed as input of the future phases of the CTA process. Different visions can be compared and combined into a realistic vision that is shared among all actors.
4. Constructing such visions in cooperation with technology developers demands learning among the them. Learning in this context means that the technology developers take other perspectives into account when designing the technology.

What could be concluded from these four reasons is that the visions of technology developers are crucial is gaining insights into the development of the technology at an early stage.

Figure 2.1 shows the steps of the CTA process with vision assessment which leads to the guiding visions. CTA starts with phase 1 in which societal actors are not aware of the developments of the technology and want visions to reflect upon. In this case the RIVM is not aware of the developments and need visions to reflect upon.

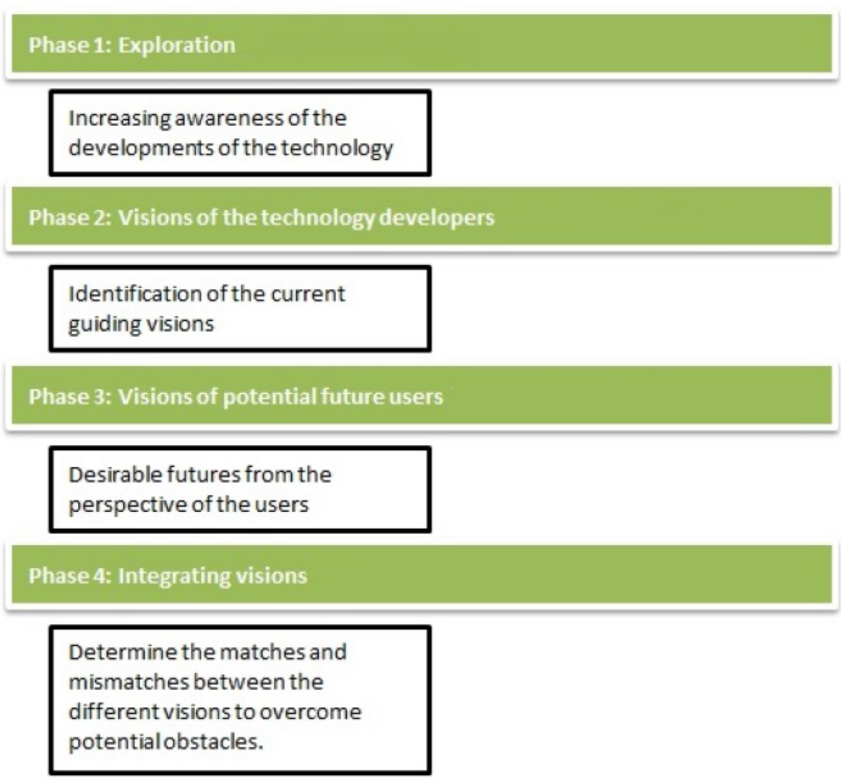

Figure 2.1: The CTA process (adopted and based on Roelofsen et al. (2008; 2010a).

In phase 2 the visions of a desirable future from the perspective of technology developers are investigated. In phase 3 the visions of a desirable future from the perspective of technology users are identified. In phase 4 the visions are compared, matches and mismatches can be identified and a stable vision of the future can be made.

2.4 Conceptual Model

In this study the focus will be on phase two and phase three of the process described in Figure 2.1, namely on gaining insights into the visions of the 3D printing developers and users. A conceptual model is formed to gain structure and insights in the concepts that are relevant to this study. The conceptual model, shown in figure 2.2, is based on a study of Roelofsen (2008), that explores the guiding visions toward ecological genomics, and Grin and Grunwald (2000). The following four concepts of the assumptions underlying the guiding visions are distinguished:

1. Current state of knowledge and technology
2. Purposes to be fulfilled
3. Interpretation of relevant contextual aspects
4. Normative premises

According to Roelofsen et al. (2008) the underlying assumptions are divided into 'first order notions' and 'second order notions'. Getting insights in the first order notions may result into incremental changes in problem solving strategies. Critical reflection on the second order notions result into deeper insights in problem structures and may lead to effective solutions. The first two concepts cited above are first order notions, for example solution assessments and problem definitions. The other concepts are second order notions, which are for example worldviews, value systems and preferred social order. The four concepts of the assumptions underlying the guiding visions are further explained and elaborated below.

2.4.1 The current state of knowledge

This concept refers to the current state of knowledge and technological developments. It addresses the varying applications of 3D printing and the fields in which 3D printing is used. Furthermore, it addresses the current developments of 3D printing. An example of a current state of knowledge is the fact that 3D printing could be used in the health care to print customized implants.

2.4.2 Purposes to be fulfilled

Purposes to be fulfilled cover the expectations and objectives of the actors about future use of the technology and what technology developments are relevant in the perspective of the actors. The assessment of the objectives uncover the reason why actors have certain expectations. An example of a purpose to be fulfilled is the use of 3D printing for animal testing.

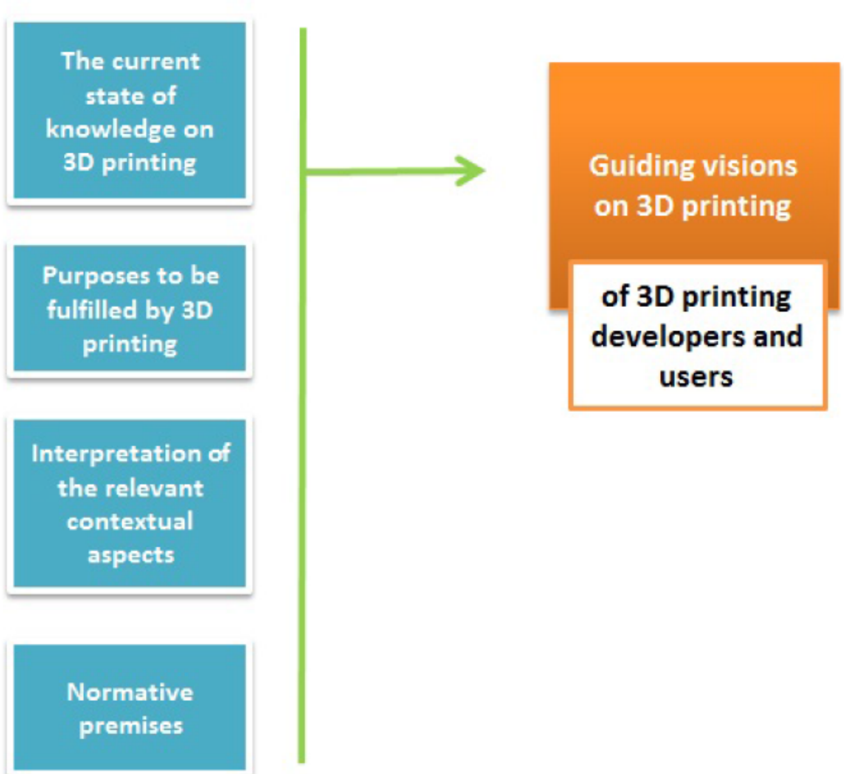

Figure 2.2: Model of guiding visions of 3D printing developers and users

2.4.3 *Interpretation of the relevant contextual aspects*

The concept of the relevant contextual aspects refers to the circumstances and conditions that form the future applications. There might be some aspects needed to form the application in its context. Probably this will entail some normative or empirical problem definitions that need to be challenged before further development is possible. In addition, this concept also refers to the possible impact 3D printing has on environment and society.

2.4.4 *Normative premises*

The fourth element that underlies guiding visions are normative premises. This refers to norms, values, and the motives that the actors have in regard to the development of 3D printing. It consists of the preferred course of events and the ideas of how the world should look like when 3D printing becomes an ordinary technology.

When the current applications and developments of 3D printing are known and challenges that need to be solved in order to fulfill the expectations about future use are identified, it will provide insights in the development of 3D printing and the possible impacts on sustainability, society and safety.

2.5 Research questions

The following main research question is derived from the conceptual model, the central question in this study is:

What are the guiding visions held by the 3D printing developers and users concerning the applications and their impact on sustainability, safety and society?

In order to provide an answer to the main research questions five sub questions are formulated. The last four sub questions are based on the four underlying assumptions that construct guiding visions. As it is unknown yet who are the technology developers and users it is first important to map these actors before the underlying assumptions will be identified. Since this study is conducted in The Netherlands we only focused on mapping of 3D print developers and users in the Netherlands. The sub questions are formulated as following:

1. *Which companies and universities are working on the development of 3D printing and which companies or institutes use 3D printers in the Netherlands?*
2. *What is the current state of knowledge and technological development of 3D printing and of its applications?*
3. *What are the purposes to be fulfilled with 3D printing, according to its developers and users?*
4. *What conditions are required to develop future 3D printing applications, according to its developers and users?*
5. *What are the normative principles according to the development of 3D printing held by its developers and users?*

3 Methods

This chapter provides an overview of the methods used in this study. The process to gather guiding visions of 3D printing developers and users included a small desk study and qualitative study based on semi-structured interviews. Below the data collection and the data analysis will be discussed in more detail.

3.1 Desk Study

3.1.1 Data collection

As a first step towards guiding visions a desk study was conducted. The desk study was not profound, because the aim of the data analysis was to get a first impression of 3D printing and create a knowledge base that is needed in the interviewing process. Without this knowledge the chance of misunderstandings between researcher and interviewee more likely, which could influence data quality significantly.

In order to find relevant literature, different sources of literature have been explored. Scientific peer reviewed literature is the medium in which scientists communicate their research and ideas and was therefore an interesting medium to explore. Consequently, databases as Scopus and Science Direct were used for this purpose. Additionally, the websites of different Dutch research institutes like 'the Rathenau Institute' and 'Stichting toekomst der Techniek' were consulted for relevant literature.

Moreover, Internet searches with Google and Google Scholar were performed. To find relevant literature with these search engines key words as, '3D-printing applications', 'sustainable 3D-printing applications', 'impact of 3D-printing', 'additive manufacturing', 'organ printing', 'tissue engineering' were used.

3.1.2 Data analysis

During the desk study several literature was found that contained information about 3D printing. The gathered literature was analyzed in order to provide an overview of the current 3D printing technologies, a first impression of the Dutch experts on the subject, an identification of relevant 3D printing domains and an overview of the developments per 3D print domain. In this literature we specifically looked for the following subjects: '3D printing applications', '3D print technologies', 'visions about the current state of the technology', 'recent developments', 'issues that might hamper further development', 'concerns about 3D printing' and 'impact of 3D printing'. Literature that contained information about one or more of these subjects was saved in a literature database.

3.2 Qualitative study: interviews

3.2.1 Sampling

Qualitative research mostly focuses in depth on a relatively small sample, therefore it is important to select the participants for our interviews purposefully (Pattons, 1990). Pattons (1990) stated that 'the logic and power of purposeful sampling lies in selecting information-rich cases for study in depth. Information-rich cases are those from which one can learn a great deal about issues of central importance to the purpose of the research.' In this study we used two sampling techniques to obtain a purposeful sample.

The first sampling technique is called maximum variation sampling. This sample strategy aims to capture and describe the central themes or principal outcomes that cut across a great deal of participant or program variation (Pattons, 1990). In our case the 3D print applications are very divers and therefore it was important to obtain a group of participants that covered the wide range of 3D print applications. Earlier in paragraph/section 2.3 it is described that the most important actors in an early state of the innovation process are technology developers and users. Because the users of 3D printers also become producers it was needed to clarify who the technology developers and who the users are. In this study 3D printing developers are the actors that make the 3D printers and researchers that, for example, try to find new materials to print with. Technology users are actors that use 3D printing to develop their product or provide a service. Additionally, it was decided to include the actors that could be sampled by one of the four domains in which 3D printing is used: (manufacturing) industry, consumer, healthcare and food. These domains were derived from the desk study and are further explained in the results. To identify the relevant actors, websites of different Dutch universities were explored to find researchers that conducted studies with 3D printers or on 3D printing. Additionally, a search on the internet was conducted to find companies that work with 3D-printers. Another strategy that was used to find the leading companies in the 3D printing market was to approach the companies that sponsor 3D print conferences. It is evident that the sampling of respondents benefited of the results of the desk study. In practice the sampling of respondents and the desk study sometimes intertwined.

The second sample technique is called snowball or chain sampling. We used this approach to locate the important actors in the field of 3D printing and obtain addresses of actors which were not findable on internet. After every interview the interviewees were asked if they know other actors in the field of 3D printing, which were interesting to interview too. This approach led to more actors that were not yet found by the other approach.

The combination of both approaches resulted in an overview of relevant actors and companies in the Dutch 3D printing domain. In Appendix 1 this overview is provided.

3.2.2 *Recruitment*

It was tried to recruit an equal amount of experts from every domain. Twenty-five actors that were sampled by one of the four domains were invited via a letter (Appendix 2) by post. When there was no response within a week, a kind reminder was send by e-mail. When there was still no response after the e-mail, the experts were contacted by telephone. Of the twenty-five targeted experts, nineteen reacted positive and were willing to participate. One participant had no time for an interview. The other five did not respond to the letter neither to their emails. Because we could not find any telephone number of these experts, they were not contacted by telephone. Appendix 3 contains a scheme with all the nineteen consulted experts and their expertise. Seven participants have expertise in industrial 3D printing, three participants have expertise in consumer 3D printing, another three participants have expertise in healthcare 3D printing, two participants have expertise in food printing and four participants have expertise in both industrial and consumer 3D printing. One extra participant was interviewed which could not be sampled by one of the four domains, but recently wrote a book that describe some developments of 3D printing and therefore seemed interesting to interview too.

3.2.3 *Semi-structured interviews*

To gain insight into the elements underlying guiding visions, semi-structured interviews were conducted. Semi-structured interviews are interviews whereby not all the questions are already known but only a topic list of the most important subjects and questions are known by the interviewer, depending on the answers follow-up questions could arise to explore a subject or topic in-depth (Britten, 1995). Semi-structured interviews were selected on the consideration that they are well suited for the in-depth exploration of the perceptions and expectations of the interviewees (Louise Barriball & While, 1994). In this study, the perceptions and expectations of 3D developers and users regarding the development of 3D printing were explored in-depth.

The interviews were conducted according to a manual developed by the first author of this report, which could be found in the appendix. According to the manual the interviewees were first asked about the research they conducted or product that they made, this gained insights in the current state of knowledge. Furthermore, interviewees were asked about their expectations of the developments of the 3D printing technology how their desired future look liked. To prevent the participants from being cautious with their predictions, they had to imagine year 2060, by then many current problems might be solved. Hereafter, the participants were asked what possible positive or negative implications on society they envisioned. Furthermore, questions that provide more insights into the other two aspects, sustainability and safety, were asked. At last, they were asked if they had some literature suggestions, which could be used for the desk study. All interviews were recorded with permission of the participant and during the interviews field notes were taken. The interviews were held at a place that was proposed by the interviewee, which most of the time was on the office. One interview was conducted by telephone. Most interviews lasted between the three-quarters and one hour.

3.2.4 *Data Analysis*

After the desk study and interviews were conducted, the gathered information was analyzed to provide answers to the research questions. The recorded data from the interviews has been fully transcribed. Within two weeks after the interviews the summary of the transcripts was send back to the participant(s) in order to check and give additional comments on it. Subsequently, the transcripts were coded, with the use of the coding program ATLAS.ti. This process started by reading the entire transcript to remember in which context the interview toke place. Hereafter, the transcript was coded inductively. Every sentence that seemed to contain relevant information was provided with a code that captured the essence of the quote. The transcript was reread in order to check if there were other important phrases that were missed the first time and to check if all the codes were correctly given. When all the transcripts were coded, the code list was filtered by the four families which represents the four domains of 3D printing. Every code that said something about food printing was placed in the family food printing and so on. Subsequently, within the families the codes were divided into four categories derived from the data but with conceptual model in mind. The four categories are: current state, developments, 2060 and effect. The category 'current state' captures the concept 'current state of knowledge'. The category 'developments' captures both 'current state of knowledge' and the concept 'purpose to be fulfilled', because it describes current developments and ambitions that were mentioned by the participants. The category '2060' captures the concept 'normative premises' and also 'purpose to be fulfilled', because it describes how a desired future looked like according to the participants. The category 'effects' captures the concept 'interpretation of the relevant contextual aspects', because it describes what impact 3D printing might have on the three different aspects. In Appendix 4 for every domain a coding scheme is provided.

3.3 Ethical considerations

Before the interviews started, the participant was asked permission for recording the interview, with the consequence if a participant did not agree, the interview was not recorded. However, this was never the case because every participant agreed to record the interview. In order to guarantee complete anonymity, all the participants has been given a number. When referring to them in this study, only the number and expertise is given. Only the researchers of this study know which number belongs to which participant.

4 Results

In this chapter the results of our limited desk study and qualitative study are outlined. The results of the desk study will provide a short introduction to 3D printing, as it was in fact our point of departure for the qualitative interviews. As stated more exactly in the methodology the desk study aims to provide an overview of the current 3D printing technologies , an identification of relevant 3D printing domains and an overview of the developments per 3D print domain. This last information is highly needed as it formed the baseline of understanding and questioning the participants in our qualitative study. The qualitative interviews in the second section of this chapter go a bit deeper, as departing from the results of the desk study in this chapter, we will ask the respondents about their vision on 3D printing in the domain they represent.

4.1 Desk study

4.1.1 Introduction: literature about an emerging technology

3D printing is a relatively new technology and the academic peer reviewed literature about its possibilities is not abundant. This does not imply that there is no information available however. Relevant information is provided by consultants like Gartner, Mckinsey and Wohlers. It is especially this last firm that has compiled a report that is considered to be the most relevant source of information about 3D printing. Interestingly the former Dutch Minister Willem Vermeend also composed a book and a website called 'De wereld van 3D printen' (the world of 3D printing). Moreover, popular news sites regularly publish small articles about 3D-printing and dedicated websites that publish 3D printing news exist.

The fact that 3D printing is regularly the subject of popular media is indicative of the expectations and the extent the technique appeals to people's imagination. A good illustration of this fact is provided with the so-called hype cycle of emerging technologies (Figure 4.1). This hype cycle illustrates how emerging technologies and trends are evaluated by their degree of 'maturity' and to what extent the market and the public accept them. Technologies that are at the top of the curve are currently a hype. After this peak the graph declines, which means that the expectations become gradually more realistic and the defects of the technique are recognized, where after the technology can get more advanced and in the end could be productive.

For 3D-printing holds that different domains of application have different positions on the hype cycle. Consumer 3D printing is on top of the hype, enterprise 3D printing and 3D scanning has already passed it, while for 3D bioprinting systems the hype has yet to come. These differences in perceptions and maturity of the technique for different 3D printing applications provide a relevant context as it will influence both the results of our desk and qualitative study.

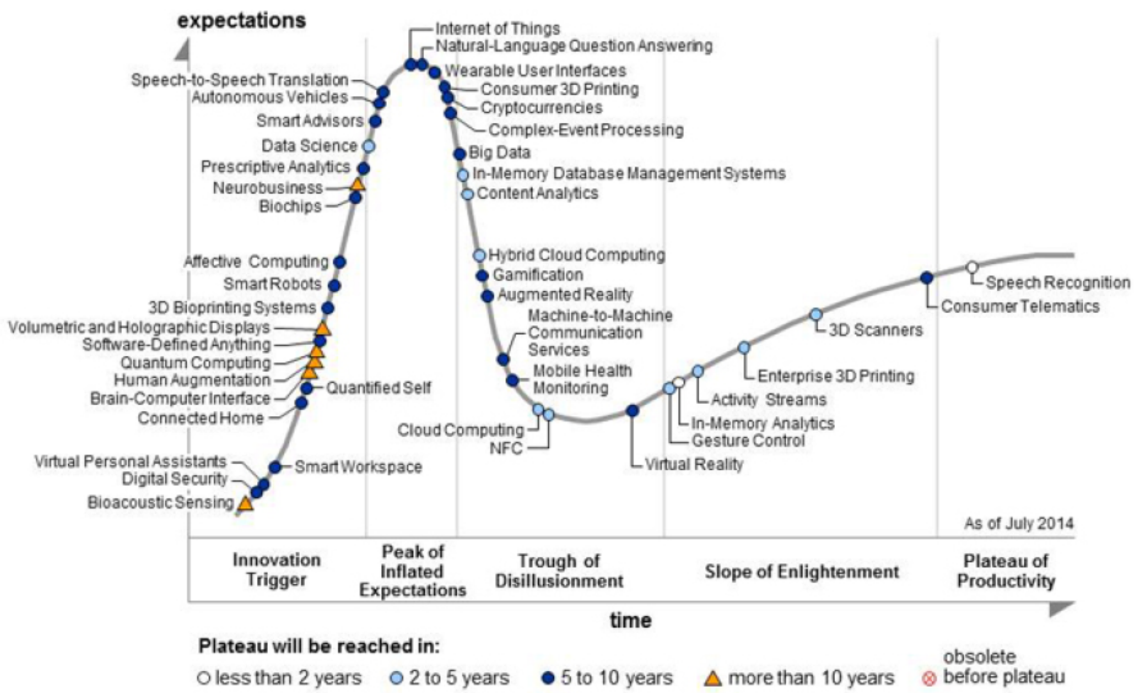

Figure 4.1. Hype cycle of emerging technologies

4.1.2 *Four different domains of application*

3D printing is a collective name for different technologies that work with an additive way of manufacturing. During our limited search for relevant literature it appeared that 3D printing was a very wide concept and the technique is used in different domains. Only focusing on the narrow concept 3D printing, without a discussion of the domains of application could provide an incomplete overview of 3D printing. The book 'De wereld van 3D printen' (the world of 3D printing) by Vermeend (2013) provides a good overview of the different application domains and the web version of this book is continuously updated. Therefore, this source is used as an entry to provide the most relevant domains of 3D printing. Moreover, the hype cycle, as presented earlier, already made a rough classification in different 3D printing application domains, which is consistent with the findings by Vermeend.

The first relevant classification in the application of 3d printing is by the type of users. These either are professionals or these are citizens, who use 3D printers when they are not at work. Consequently, there are several advanced 3D printers, which are used mainly by the industry to build prototypes and produce goods. Next to these advanced industrial 3D printers, there are relatively simple 3D printers which are especially built for consumer use. Moreover, a classification can be made in the type of professional usage. Besides industrial manufacturing processes with 3D printers, in healthcare 3D printers are used to manufacture prostheses and special bio printers are used to do research on the construction of human tissue. The last domain where professional experiments and applications take place with special 3D printers is the food industry, in which 3D printing techniques are used for the preparation of food.

In box 4.1 the most frequently used 3D print technologies are described. These techniques are predominantly used in an industrial setting.

Selective laser sintering (SLS)
In this technique, a layer of powder is deposited on the build platform, and then a laser "draws" a single layer of the object into the powder, fusing the powder together in the right shape. The build platform then moves down and more powder is deposited to draw the next layer. SLS does not require any supporting structure, which makes it capable of producing very complex parts. SLS has been used mostly to create prototypes but recently has become practical for limited-run manufacturing. General Electric, for example, recently bought an SLS engineering company to build parts for its new short-haul commercial jet engine.

Direct metal laser sintering (DMLS)
DMLS is similar to selective laser sintering but deposits completely melted metal powder free of binder or fluxing agent, thus building a part with all of the desirable properties of the original metal material. DMLS is used for rapid tooling development, medical implants, and aerospace parts for high-heat applications.

Fused deposition modeling (FDM)
A filament of plastic resin, wax, or another material is extruded through a heated nozzle in a process in which each layer of the part is traced on top of the previous layer. If a supporting structure is required, the system uses a second nozzle to build that structure from a material that is later discarded (such as polyvinyl alcohol). FDM is mainly used for single- and multipart prototyping and low-volume manufacturing of parts, including structural components.

Stereolithography (SLA)
A laser or other UV light source is aimed onto the surface of a pool of photopolymer (light-sensitive resin). The laser draws a single layer on the liquid surface; the build platform then moves down, and more fluid is released to draw the next layer. SLA is widely used for rapid prototyping and for creating intricate shapes with high quality finishes, such as jewelry.

Laminated Object Manufacturing (LOM)
A sheet of material (paper, plastic, or metal) is fed over the build platform, adhered to the layer below by a heated roller, and a laser cuts the outline of the part in the current layer. LOM is typically used for form/fit testing, rapid tooling patterns, and producing less detailed parts, potentially in full color.

Inkjet-bioprinting
Bioprinting uses a technique similar to that of inkjet printers, in which a precisely positioned nozzle deposits one tiny dot of ink at a time to form shapes. In the case of bioprinting, the material used is human cells rather than ink. The object is built by spraying a combination of scaffolding material (such as sugar-based hydrogel) and living cells grown from a patient's own tissues. After printing, the tissue is placed in a chamber with the right temperature and oxygen conditions to facilitate cell growth. When the cells have combined, the scaffolding material is removed and the tissue is ready to be transplanted.

Box 4.1: Current 3D printing technologies. Source: McKinsey (2013)

4.1.3 *Industrial printing*

Industrial printing or additive manufacturing is a wide concept, in which very different activities find its place. A useful distinction is between products and services. Products include the 3D printers, materials and aftermarket, which means the market for spare parts, accessories, and components. Services include products that are made by service providers, system maintenance contracts, advertising, conferences etc. (Wohlers, 2014)

4.1.3.1 Characteristics

Wohlers Associates (2014) report on a few very relevant characteristics of 3D printing. The first is that in the literature about (industrial) 3d printing there is a change in the terminology use. The term Rapid Prototyping Manufacturing mainly occurs in studies from the nineties while more current studies use the term Additive Manufacturing when referring to 3D printing. Several authors state that this indicates a shift from a prototyping technology towards a manufacturing technology (Vermeend, 2013; Diginova, 2013; Mc Kinsey, 2012). This corresponds with the position on the hype cycle. This shift from prototyping to manufacturing has strengthened the growth of industrial 3D printing, because the production of end parts has a larger market than the production of prototypes. The compound annual growth rate (CAGR) of additive manufacturing in 2013 including revenues derived from all the production and service grow with 34,9 % to 3,07$ billion (Wohlers, 2014). These numbers show a major economical increase in the additive manufacturing industry.

A second characteristic Wohlers Associates (2014) report about is that 3D printing is economically suitable and therefore applicable, for parts that are low in volume, complex and small. They described seven scenarios in which 3D printing could be more cost-effective then other manufacturing technologies, namely when: the product is to expansive to manufacture, the time between the initiation and completion of a production process is too long, inventories have high costs, one is completely reliant on one supplier, one operates on remote locations, one have high import/export costs and when the functionality of a product needs to be improved. Consequently, in not all cases 3D printing can be done cost-effectively. Therefore for every product a cost-benefit analysis should be conducted in order to investigate if 3D printing is a better manufacturing technology. The outcome of such analysis applies only for that product and is not generalizable to others (Wohlers, 2014).

A third characteristic reported is the effect of 3D printing on the use of resources (sustainability) and environment. Wohlers Associates illustrate this with a study that sought to compare metal 3D printing to conventional manufacturing and evaluate the entire product life cycles, from the raw material phase through the service phase. The study chose a particular part and produced it with 3D printing and a conventional technique, from the equations they concluded that for this particular part, 3D printing reduced 15 times the raw material energy use and 8 times the manufacturing energy use. This example shows that 3D printing could reduce the overall energy use. Though, this could not be generalized for 3D printing per se, just like the cost-benefits analyses the life cycle energy consumption should be evaluated case-by-case.

In addition, 3D printing is likely to have a positive effect on the environment. Campbell (2011) stated several reasons why 3D printing might create advantages for the environment. Firstly, due to more digital designs transfer around the world and the possibility that companies will print the products nearer to where it is purchased and used, it is possible that the carbon footprint of manufacturing and transportation reduce. Secondly, Campbell states that 3D printing may also reduce the use of toxic chemicals in manufacturing processes. Moreover, 3D printing could reduce the difficulty and expense of the disposal of these chemicals, as well as reduce the overall need for their production.

4.1.3.2 Shortcomings that delay growth

Yet the most of the authors recognize that there are many constraints which hamper the further growth of industrial 3D printing. These constraints are all technical in nature. Vermeend (2013) stated that 'the technology is mainly in its infancy and need some fundamental technical improvements'.This resembles the message formulated by DigiNova, a project funded by the European Union, aimed at assessing the current status and potential of Digital Fabrication, which 3d printing is a part of (DigiNova, 2013). According to Mc Kinsey (2013) high material costs and low building speeds could constrain the wide-scale adaption of 3D printing. If these limitations do not improve, it is expected to substantially lessen the economic impact of 3D printing.

4.1.3.3 Forecasts

For the upcoming years Wohlers Associates (2014) made a forecast about the growth of the industrial printing/ additive manufacturing market, they expect a strong growth over the next several years. They forecast that by the time of 2016 the products and services exceed to $ 7 billion worldwide. By 2018 it had risen to $12.5 billion and by 2020 the additive manufacturing industry is forecast to exceed to $ 21 billion. They even expect that in the far future industrial 3D printing will exceed to 2% of the global manufacturing market, which is $210 billion. Industrial 3D printing is therefore not seen as a hype and has a future to become a common manufacturing technique.

In the literature different statements were found about the impact of 3D printing as a manufacturing technology. Some authors state that 3D printing could be a new industrial revolution which might substitute conventional techniques (Berman, 2012; Birtchnell et al., 2013; Huang et al., 2013; Anderson, 2013), while others are more reserved about the future impact of 3D printing (Vermeend, 2013; Wohlers, 2014).

4.1.4 Consumer 3D printing

According to Wohler Associates (2014) consumer 3D printers are 'Additive Manufacturing systems that sell for under the $5,000'. The past few years many fabricators of consumer 3D printers came on the market. At this moment, according Wohlers Report (2014) it is believed that 250 companies build consumer 3D printers, with mostly the FDM technique. The increasing interest of society could be seen in the number of purchased consumer 3D printers presented in Table 4.1, the sales grew with 104% in 2013.

Year	# purchased consumer printers
2011	24265
2012	35508
2013	72503

Table 4.1: Purchased consumer printers per year. Source: Wohlers (2014)

4.1.4.1 Characteristics

The makers movement, a current trend, is mentioned many times to address why 3D printing is popular among hobbyists or so-called 'Makers'. This movement describes that people increasingly develop the need to make things on their own (Anderson, 2013). Makers are inventors but not with a special economical purpose. They just want to turn their ideas into physical objects, for example jewelry or cases for smartphones. A 3D printer is ideal to turn those ideas into physical objects. Consequently, the makers movement is an important driving force behind the development of consumer 3d printing.

A great supporter of consumer use of 3D printers is Chris Anderson, author of the book 'Makers, The New Industrial Revolution'. In his book he stated that the biggest chance is not the additive way of manufacturing, but by whom things are made. He thinks that everyone is able to print things in the nearby future and therefore expects that in the future every consumer makes use of 3D printers. Britchnell (2012) has a more conservative view, he only says that consumers could have 3D printers at their home in the future, but does not say whether this is realistic or in what extend this could be. Overall it could be said that the majority of the authors on consumer 3D printing acknowledge that due to 3D printing manufacturing becomes more accessible for consumers. It remains unclear to what extent consumers will use this opportunity.

4.1.4.2 Shortcomings that delay growth

Wohlers Report (2014) stated that printers for consumer printing mostly do not meet the quality standards of product development and manufacturing and therefore need the technological developments that were already mentioned under industrial 3D printing. McKinsey (2013) also stated that consumer 3D printing needs technological improvements, but also mentioned that high material costs are a limitation for the development of consumer 3D printing. Though they expect that by the time of 2025 both the technical and material cost limitations are improved.

4.1.4.3 Forecasts

In literature no clear line about the future use of consumer 3D printing was found. Most literature has great expectations, however, often is spoken about consumer use which not necessarily means the use of consumer 3D printers, it could also refer to consumers who order 3D printed objects online or use industrial 3D printers in nearby copy shops.

McKinsey (2013) envisioned that by the time of 2025 3D printing has an economic impact of $230 to $550 billion per year. They stated that the largest source of potential impact would come from consumer uses and they thought it is possible that many consumers will use consumer 3D printers at home by 2025. The following quote contains the vision of McKinsey (2013) about the consumer use of 3D printing.

'3D printing could have meaningful impact on certain consumer product categories, including toys, accessories, jewelry, footwear, ceramics, and simple apparel. These products are relatively easy to make using 3D printing technology and could have high customization value for consumers. ….. It is possible that most, if not all, consumers of these products could have access to 3D printing by 2025, whether by owning a 3D printer, using a 3D printer in a local store, or ordering 3D-printed products online. We estimate that consumers might 3D print 5 to 10 percent of these products by 2025.'

4.1.5 Healthcare printing

For healthcare printing our limited desk study resulted in only a few useful pieces of literature. Consequently, we cannot follow the same structure that we used in the discussion about consumer and industrial 3D printing (characteristics, shortcomings and forecasts). Specifically the literature about forecasts is missing. On this part a stronger reliance on the qualitative study is needed.

4.1.5.1 Characteristics

Healthcare printing can be categorized into medical and bio printing or tissue engineering. Medical printing is defined as 'applications which range from non-custom, off-the-shelf implants to custom models for surgical planning, custom implants and prosthetics, and personalized instruments for surgical procedures' (Wohlers, 2014). Bio printing or tissue engineering is defined as a 'rapidly growing interdisciplinary field involving the life, physical and engineering sciences and seeking to develop clinical therapies for the repair, maintenance, replacement and/or enhancement of biological function' (Nerem, 2010).

4.1.5.2 Shortcomings that may delay growth

According to Wohlers (2014) the biggest shortcoming in healthcare printing is the lack of approved materials. They explain that the current materials that are available have passed certain standards for biocompatibility, the ISO 10993, which is a biological evaluation of medical devices. For example, a test should be conducted in order to test the interactions with blood. They stated that when a raw material is successfully tested it does not mean that the material could be used for healthcare applications without further more-product-specific testing. A prerequisite for further research is that the manufacturing process should be controlled. This ensures that the manufacturing process will yield parts that are suitable for a certain application. Since, the 3D printing process is uncertain and not yet in control, standards for the 3D printing process are needed to ensure appropriate use of materials and safe medical devices.

4.1.6 Food printing

The domain of application we found the smallest amount of literature about is food printing. For this domain the structure we used to discuss our findings is not applicable; we have to improvise. For this domain also hold that a stronger reliance on the outcomes of our qualitative study is needed. Nevertheless, this is a very relevant domain as several 3D food printers already exist and the expectations about the future of 3D food printing are high. The following quote by Daymon Kayzee (2014) provides a good illustration of these high expectations:

'Simply stated, you get what you put in. Food can be broken down into three main components: protein, carbohydrates, and fats. One day the technology will be advanced enough to simply put a custom amount of these nutritional categories into the printer, add custom flavors, and choose a type of food to print.´

Literature did not provide a clear definition of food printing. Vermeend (2013) describes the process of food printing, which could be used as a definition, as extruding pureed and melted ingredients which results into edible food. In box 4.2 we provide a web based article about 3D food printing that illustrates the state of the art in food printing and at the same time provides shortcomings that may delay growth.

There have been a few different food printers that have come to the stage, like the Foodini, Candy, and the ChefJet from 3D Systems. As amazing as these machines may be, they don't quite fulfill the dream of a Star Trek replicator capable of delivering fully-cooked meals on demand. The Foodini, for instance, can extrude food pastes into complex shapes, but the food must either be edible when raw or cooked after printing. The ChefJet, on the other hand, can make some of the most beautiful pieces of food imaginable, but it's limited to sugar-based structures. As much as we might like to, we can't eat candy for every meal and, so, we await a 3D printer that both prints the food and cooks it (and one that isn't reserved for cosmonauts). F3D is a food printing research project that has that goal in mind.

Four undergraduate students from the Imperial College London (Hillel Baderman, Jacob Watfa, Francis Nwobu, and James Clarke) have modified existing RepRap 3D printing technology to create a food printer capable of 3D printing and cooking a complete dish. In creating F3D, pronounced "fed", for their third year final project in Mechanical Engineering, the students combined the best aspects of various paste extrusion ideas, including Richard "RichRap" Horne's Universal Paste Extruder, Hod Lipson's Fab@Home paste extrusion system, and Thingiverse user keesj's Simple Paste Extruder. To control the printer, they decided on the DUET and DUEX4 bundle, capable of handling up to five different extruders. Finally, to cook the food, F3D relied on the tried-and-true technique of Hasbro's Easy-Bake Ovens, using a halogen oven.

With a budget of £1,200, the students were able to construct a machine that can 3D print three different ingredients with three extruders and cook the entire dish with the halogen oven for just £1,145.19 (about $1900). While it's still in the prototype stage, F3D proved its potential by 3D printing a pizza – made from dough, cheese, and tomato puree – and cooking it in just 20 minutes.

Even if the 3D printer is still relatively simple at this stage (compared to the skills of a human chef), it is impressive, nonetheless. In its most basic application, it could easily become a sophisticated toy for kids and, in its most actualized form, F3D becomes a powerful appliance from the future. F3D's creators have published their entire design and build process online, so it's only a matter of time before it becomes modified by others or even fully appropriated by large corporations ready to take advantage of well-meaning students.

Box 4.2: F3D 3D Food Printer is Really Cooking

4.2 Qualitative study: interviews

In the second section of this chapter, the results of the interviews with different developers and scientist are outlined. As from the desk study appeared that 3D printing could be divided in four application domains, this part is structured according to the same four domains. For each domain the current state of technology is described which provides insight in the current applications and drawbacks. Subsequently, the desired developments held by the interviewees are described. Then the visions and opinions of the interviewees about the future use of 3D printing in that particular domain is described. At last, the envisioned impact on sustainability, safety and society is outlined. At the end of every described domain a figure is presented which covers the main results.

4.2.1 Industry

4.2.1.1 Current state of industrial 3D printing

While 3D printing is still predominantly used for prototyping, all interviewees see a shift from rapid towards additive manufacturing. They mentioned that 3D printing is no longer only used for production of prototypes, but evaluates towards a manufacturing technology which also makes end products. Due to this shift, 3D printing becomes more attractive for different industries.

In order to explain why industrial 3D printing is of interest for many industries the interviewees provide a variety of advantages. The majority of them appoints freedom of design as the most important advantage. This advantage implies that objects can be customized and previously impossible shapes can be made. Especially, in the aerospace and automotive industry these advantages come in handy. According to some participants (Int. 1, 2, 3, 8, 10, 11), these two industries already use 3D printing technology to redesign parts of aircrafts or cars to make them stronger, lighter or more efficient to use. Another frequently named example of an industry that benefits of the freedom of design by 3D printing is the dental industry.

Another, often mentioned reason why the industry is willing to adapt this technology is the minimum waste of material. With traditional manufacturing techniques a large percentage of material will be thrown away as waste. With 3D printing, due to the additive way of manufacturing, less material is needed to build a product and almost no waste is generated. However, four participants (Int. 3, 4, 8, 12) addressed that not every 3D print technology generates zero waste. The material powder, which is not fused together with SLS type of technologies, is only partly reusable. In the case of polymer powders between the 20% and 60% could be reused for approximately three times, thereafter it is thrown away as waste. However, in the case of metals the powders can be reused for almost 100 %. Eventually, with one kilo material almost 1 kilo of products can be made, whereby companies can save money on materials.

Despite of these advantages, the current state of the technology is not yet applicable for the whole industry, as it still has many drawbacks. All participants indicate that the limited types of materials that can be used in 3D printing is a drawback compared to classical manufacturing technologies. For example, one of the experts in material development (Int. 4) explained that injection molding had more different types of material when compared to 3D printing. Consequenly, with injection molding it is possible to choose between different compounds for each material type. He thought that when the pallet of 3D print materials becomes larger and more compounds are created the more applicable 3D printing becomes.

Another drawback of 3D printing, which is mentioned by almost all interviewees, is about the unknown properties of products after the print process. For example, with a conventional technique as injection molding, it is known how the properties of the material change after heating, and how this could be influenced to strengthen the product. However, in the case of 3D printing, interviewees often complained that the properties of the printed products sometimes are not as intended. Therefore, it is not guaranteed that printed products have the same properties as when they are made with classical manufacturing techniques. The following quote illustrates the potential of 3D printing and how the uncertainty about the product properties is a drawback for the industry.

> *'For airplanes it is important to make things as light as possible and this new technology has an excellent means to the reduction of weight, because the current designs are depended on the current fabrication technologies and their limitations that are entailed. And for some parts in the airplane 90% of the material is discarded, that costs a lot of resources, many material and many processing time and those parts could be perfectly made with 3D printing. At this moment we only see a few printed parts end up in airplanes and the mean reason is the fact that the process is not yet in hand, you cannot assure that the mechanical properties are good enough to use the object. Thus the advantage of 3D printing is getting lost, because you cannot get the strength which you can get with classical technologies.' (Interviewee 11: expert in 3D printing and aerospace)*

A related drawback correlates with the fact that many new 3D printers come on the market, three interviewees (Int. 1, 2, 8) even call it a proliferation. They experienced that although these new 3D printers could bring some innovative solutions for former problems, it also bring some disadvantage, because every printer has its own qualifications and features. At this point, it cannot be guaranteed that the same object, printed on two different 3D printers, are completely equal to each other. Therefore, some participants (Int. 1, 2) want a more standardized process, in order to compare relative performance of 3D printers. However, one interviewee (Int. 11) thought it might be too early to standardize the process; he wants to wait until the best printers are on the market. The following quote explains the consequences of a non-standardized process.

> *'When you print an object at two service providers, you will see that those objects always differ. Sometimes the object from the first service provider is better, sometimes the object of the other provider is better. The quality of the objects is unpredictable. For us it is just weird, but imagine when it is a heart or a part for your car or a bullet, than you have to know that the object is just safe to use and does not fall apart.' (Interviewee 1: Expert in CAD engineering)*

Another issue that was mentioned many times(Int. 3, 6, 7, 8, 10, 11) during the interviews is about the low position of the Netherlands compared to other countries as it comes to developments and investments in industrial 3D printing. According to the interviewees most innovations and investments in 3D printing are in America, Germany, England and Belgium. However, the Netherlands has a lot of potential to be part of the top, because it has a strong high tech industry. The participants provided as an explanation that the industry and investors in The Netherlands have a wait-and-see-attitude. They do not invest yet in 3D printing because the investors have their doubts about the success of the technology. Furthermore, it was mentioned by two interviewees (Int. 3, 10) that in other countries the government invests a lot more in this technology when compared to the Netherlands. Although, one interviewee (Int. 8) thought it was the responsibility of the industry to get on the top, they all agreed that the government could do more to stimulate 3D printing in the Netherlands. One way that was proposed by some interviewees (Int. 5, 8, 10, 11) was to combine the knowledge in the Netherlands and work together to close the gap. The following two quotes exemplify interviewees who think that The Netherlands should work itself up to the top of the 3D print industry.

> *'If it is up to us, when we take a look at the world market than the Netherlands has a lag and with this industrial application (metal 3D printing) we think that when we combine our forces together in the Netherlands, we could bend it into a lead position.' (Interviewee 8: developer of a metal 3D printer for industrial use)*

> *'It is a matter of money; we didn't choose to invest in it and did other things. Countries as Belgium are far beyond we are, just like Germany and also England.... And this results in that Belgium and Germany like this state of being and only tell partly about the innovations and the other part they do not want to say, so they keep the work and the knowledge. So when the Netherlands do not solve the problems together, we keep lagging behind, because the others will never tell the state of art. The only way to be part of the leading group is to solve the problems on our own.' (Interviewee 11: expert in 3D printing and aerospace)*

4.2.1.2 Developments in industrial 3D printing

Some experts explained that the industry is especially interested in high quality products, which means products that are made with expensive material such as different metals. Metal printers therefore are of interest in many industrial areas. At this moment, there are already some metal printers on the market. However, these printers are not very reliable; it often happens that it fails to print an object. For professional use it is not acceptable that products fail, therefore research is done to acquire more knowledge about the 3D printing process and about material properties.

As earlier stated the pallet of materials suited for 3D printing is very limited. Therefore, the focus will be on the development of new materials in the coming years. An expert in 3D print material development explained that in the first place attention will be given to the modification of approved materials for classical fabrication techniques as injection molding, because it takes long to get completely novel materials on the market. With some adjustments, earlier approved materials might be possible to use for 3D printing. Furthermore, research is done on the reusability of polymer powders, some interviewees (Int. 4, 5, 6, 8, 11) envisioned that these type of powders in the future could be reused for more than 15 times instead of the three times that is currently possible. Next to the research on the expansion of the types of materials, research and the industry try to develop systems for the recycling of plastic into new print material. This was a desired development among many interviewees.

Another important development that was mentioned many times was the development of a multi material printer (Int. 1, 2, 3, 4, 5, 6, 8, 9, 12, 13, 14). Many functional end products are built with more than one type of material, therefore multi material printing was desired among many participants. It is possible that different 3D printing technologies have to merge in order to build such a printer. When such a printer will be on the market was hard to say.

4.2.1.3 Desired future use of 3D industrial printing

Most participants expect a future in which the manufacturing industry uses a combination of 3D printing and other manufacturing technologies for the production of goods (Int. 2, 4, 7, 8, 9, 10, 11, 12). They do not see it as an advantage to produce everything with 3D printers and think that some classical manufacturing technologies are so efficient that 3D printing will never be able to substitute these technologies. They envisioned that products which can be made in large series and do not have to be customized, as disposable plastic cups, will continue to be made with classical technologies. According to them 3D printing will only be used for the production of small series and for production processes in which the freedom of design is an important factor. This last factor may be the result of adaption to the preferences of the consumers or by the adaption to the function of the product. The aerospace and automotive industries are mentioned as examples of industries which will use 3D printing to manufacture certain parts in the future. The following quote illustrates why 3D printing may never fully substitute mass production.

> *'When you take a look at smartphones, those things have very complex displays and a very complex chip, you cannot print such things, that will take another 100 years. Thus it will always be a sort of hybrid system, a combination of both (classical production and 3D printing)' (Interviewee 8: developer of metal 3D printer for industrial use)*

Some interviewees (Int. 1, 2, 7, 10, 11) consider it possible that industrial printers will be used by online service providers or copy shops. Consumers could upload their designs to these service providers. The products subsequently will be printed in 'fabrics' with many 3D printers.

Furthermore, some participants (Int. 5, 6, 10) envisioned that 3D printing will contribute to a circular economy, where printed products will be recycled and fully reproduced again. A circular economy where valuable things are made out of useless things, as waste. Thereby, they envisioned, in relation to the shift of local manufacturing, that local ‘fabrics’ use local waste flows and redevelop these into print material. For example, local plastic waste could be transformed into plastic filaments.

4.2.1.4 Impact of industrial 3D printing

The changes that 3D printing trigger in the industrial domain may have many impact on the three different aspects we distinguished previously. In the following paragraphs the thoughts of the participants about the impact on sustainability, safety and society are described.

4.2.1.4.1 Impact on sustainability

All participants envisioned many positive influences of 3D printing on a more sustainable industry. Especially in the future when 3D printing becomes a common manufacturing technology, interviewees expect many changes that have positive impact on the environment.

The type of production that is expected to be taken over by 3D printing is that, which requires flexible production lines that can adapt to the demand. Compared to mass production, where large numbers of products are produced in once, 3D print production makes a shift towards on demand production. Next to that, all interviewees expect that most of the functional printed objects will be fully functional end products by the time of 2060. Subsequently, the participants expect a shift toward decentralized production. It was envisioned that 3D printed objects will be produced nearby or at the place where it will be consumed. Where traditional production happens at a large distance from the consumers, production with 3D printers will return to the places where it is consumed. The following quote summarizes this paragraph.

> *It will be logical to decentralize the production of the products that could be customized. This decentralized production only takes place with 3D printing manufacturing, thus it will be a combination of classical techniques and 3D printing. Thus, cheap products that do not have to be customized, will still be mass produced, but expensive products as scooters and cars, those products could be customized.(Interviewee 1: Expert in 3D printing engineering)*

As a result of decentralized 3D print production all participants expected that changes will occur in the logistic cycle which will have a positive effect on the environment. Instead of products that are shipped around the world, the Internet is used to transport digital designs around the world. Moreover some logistics steps could be skipped and substituted by a 3D printer. By way of illustration, when it is possible to print multi material and therefore produce functional end products, it is not needed to gather components of different manufacturers to combine them into a product. Some participants (Int. 5, 6, 8) mentioned that the distribution activities in the future will mainly concern the distribution of raw materials instead of the distribution of goods. Because raw materials are more efficient to transport, less transport is needed, which might lower the carbon footprint of transportation. The following quote exemplifies the ideas about decentralized distribution.

> *'With decentralized production you only have to distribute raw materials. This is much more efficient then distribution of finished products, thereby these raw materials are not just used for one application, but for a bunch of applications.' (Interviewee 8: developer of consumer printers)*

Furthermore, all interviewees expect that less waste is produced due to the additive way of manufacturing. Raw materials will be used more efficiently and therefore less will be wasted. Thereby, at this moment excess inventory which are not sold, are disposed. While, due to the shift to on demand production many inventory will disappear or decrease, whereby less overproduction is generated and reduces the risk of excess inventory. The following quote exemplifies the environmental benefits of 3D print production.

> *'With mass production you need global shipping, which has a huge environmental footprint when it comes to distribution. With on demand printing, local and exactly the right amounts without any stocks and also without overproduction, you could make the things you just need. Holding in the back of your mind the image of old-fashioned and analog mass production, the old industrial revolution, eventually to the last industrial revolution which I call the digital revolution, where production for the biggest part will shift to on demand, local, less distribution and a low environmental footprint due to less distribution and also eventually to zero waste.' (Interviewee 3: developer of Industrial 3D printers)*

Furthermore, as stated before, it was mentioned by some participants (Int. 5, 6, 10) that 3D printing makes a circular economy more accessible. Finite resources might no longer be thrown away, but might be reused. One of the interviewees (Int. 5) gave the example of the plastic soup in the oceans. Converting this plastic into new print material could be a great contribution to the cleaning of nature. About recycling, however, one of the participants (Int. 8) made a sharp remark. When on the long run multi material products are produced without assembly, it will be difficult to recycle them. Normally products could be disassembled, where after the different materials could be separated, however in the future different materials could be fixed together or mixed. According to the participant, this was a matter of concern, especially now the industry desires to have multi material printers. The following quotes illustrate the vision of a circular economy and a possible recycling problem due to multi material printers.

> *'When you have recycling as ambition, than you address the circular economy part and sustainability is a part of it, it all comes to circular economy. Dealing with it in a different way, where you handle cradle to cradle with sources and energy.' (Interviewee 6: expert in circular economy)*

> *'I think when you take a look at the future and we are going to print with multi material, then it will have influence on the recyclability. Because at this moment you can just disassemble products and then you can recycle in parts. When you are going to print this (pointing to a remote control) in once, than you cannot take it apart anymore. Thus when it doesn't work anymore and throw it away, yeah than we have to find a different way of recycling.'(Interviewee 8: developer of industrial 3D printer)*

4.2.1.4.2 Impact on safety

An earlier described problem, which is mentioned by many interviewees (Int. 1, 2, 3, 4, 7, 8, 9, 10, 11, 12, 14) refers to the unknown properties or qualities of the objects after it has been printed. The properties of the material before it is printed are most of the time known, however after heating it is unknown yet how these properties have changed. There are no quality standards yet that describe to what properties good objects must fulfill. Therefore, the question remains if it is safe enough to use printed objects, because it is unsure yet if these objects are as strong when compared to the same object made by classical techniques. According to some participants different standardization projects have already initiated by ISO (International organization for standardization), NeN ('Nederlandse Norm' a Dutch normalization institute) and ASTM (American standardization institute). However, one participant (Int. 11) thought it might be too early to join these standardization groups, because 3D printing is not developed enough. The printers in the future become better, therefore he thinks it might be better to wait until these printers are on the market and then describe the standards. The following quote exemplifies why the participant are reluctant to join a workshop about standardizing the 3D printing process.

> *'Frequently, we are asked to join a NeN workshop or an ISO workshop or something like that, but we don't really like to do that because it takes too much time and effort and it probably not directly comes with any results. So we keep it a little bit at distance. I also think it is a little bit too early, because at this moment we don't know yet how to make things more orderly. So you could standardize the process, however it may be better when some people who have understanding of the process eventually write down how it should be done, instead of writing it all down now and write it all over again on a later time.' (Interviewee 11: expert in 3D printing & aerospace)*

In the context of health safety, only one problem was mentioned (Int. 4, 8). The 3D printing industry is a young industry and little is known about health risks that may appear when working with 3D printers. At this moment the industry works cautiously with industrial 3D printers, especially the 3D print technologies that work with powders. One of the participants started a project in order to determine the health effects of working with metal powders. However, most participants did not think that 3D printers were more dangerous than other techniques. According to them the current regulations were strict enough and do not have to be adapted to this new technology. This is illustrated by the following quote.

> *'We are working according the highest safety standards and we have the impression that we are the only company who pays that much attention to it, when compared with other companies in this field. While this is a concern for our industry, we are a young industry and we said we don't want to have any risks. We are working with metal powder, which has a high density and of which it is still unclear what the effects are when people are exposed to it. Thus our people in the production room work with masks and when they are working with the powder they also have to wear glasses, ear protection and gloves, just to reduce the chance of exposure. We saw when we visited the fabricators of these machines, that we were actually the best of all, we saw that not everywhere people worked according these standards. I found it very surprising. Thus we started a project to gain more knowledge about the health effects,*

because later we don't want to conclude that we made something very dangerous.' (Interviewee 8: developer of industrial 3D printers)

4.2.1.4.3 Impact on society

The industrial 3D print developments have different impacts on the society. Some of the interviewees think that product designs will become more important than actual products. Due to the freedom of design products can be adapted to the wishes of the consumers. Producers can choose to offer their designs on the internet. Those designs could be partly customized by the consumers themselves. For example, a producer offers a design of a picture frame online and consumers could adapt the edge of the picture frame to their wishes. Subsequently, it may be possible that consumers choose a location where it would be printed and pick it up later that week, or they could print it at home. Production of these kind of products might no longer take place behind the walls of big manufacturing factories, but comes closer to the consumer. Some interviewees (Int. 3, 5, 7, 12, 13) therefore expected that by then 3D print production is not about manufacturing of products, but about offering designs.

Another impact on the society was about the loss of jobs. On the one hand, The Netherlands is specified in distribution of goods, due to the harbor in Rotterdam. When the shift to local production continues and less transport is needed, a few participants (Int. 8, 9, 10, 11) think it may have a big impact on the economy in the Netherlands. They mentioned that some people in the transport sector might lose their jobs. Furthermore, craftsmanship might be substitute by 3D printing and therefore these craftsman lose their jobs. For example, people who made crowns and bridges for dentists possibly will lose their jobs. On the other hand, new technologies offers new jobs. When products are printed, most of the objects still need an after-treatment. Furthermore, jobs in the software and service provider business will appear due to 3D printing. Therefore, most participants did not worry about this type of impact.

In figure 4.2, at the next page, the main results for the industrial domain have been summarized. In the figure, the findings from the expert interviews are presented. The exclamation mark indicates the subjects that need attention. The no entry sign in the figure indicates the subjects that currently hampering further development of 3D printing in this domain.

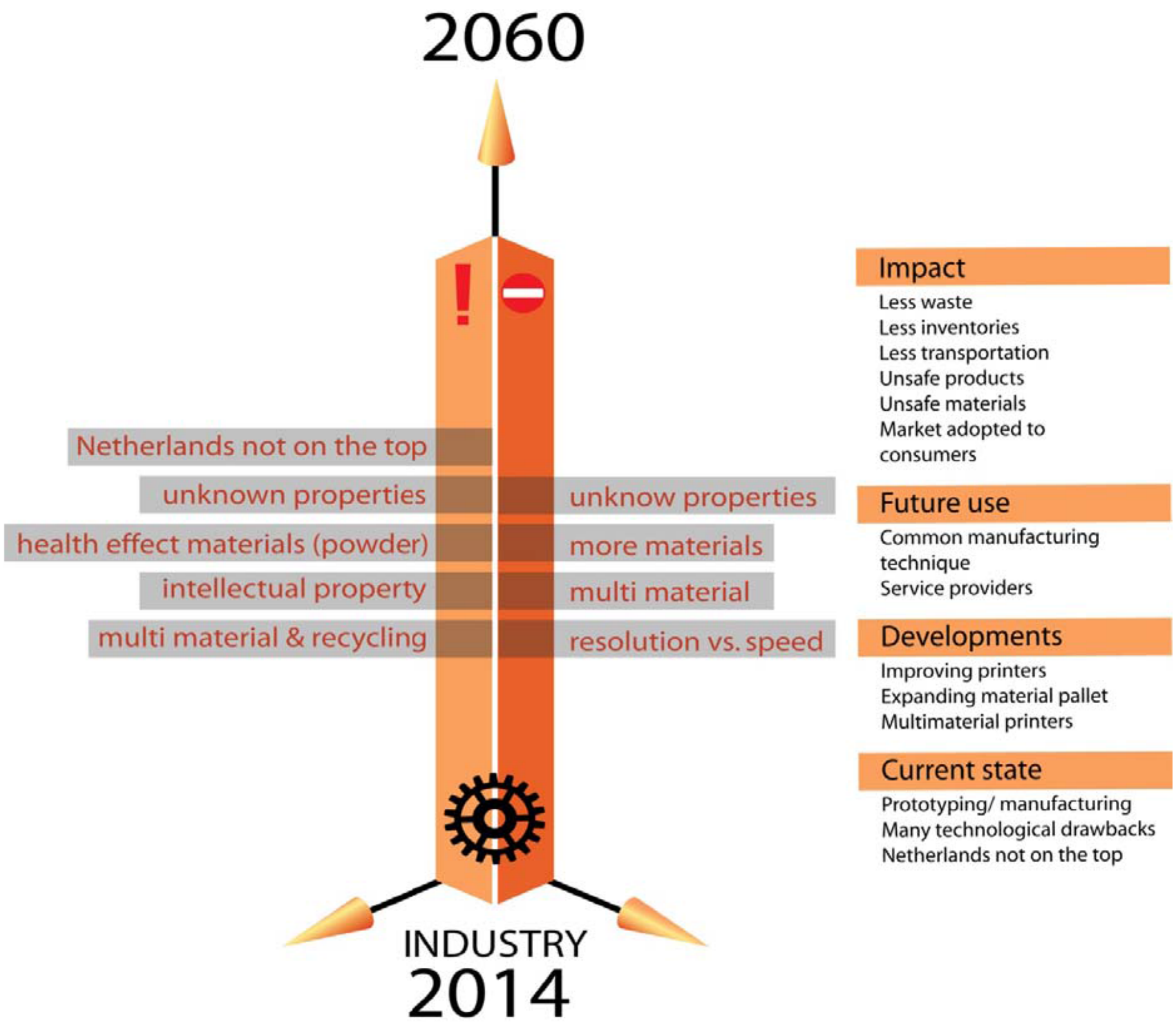

Figure 4.2: Summary of the results from the industrial domain.

4.2.2 *Consumer 3D printing*

A relatively new technology in the field of 3D printing is consumer 3D printing or personal 3D printing. In this paragraph, the development of consumer 3D printing is outlined on the basis of the interviews held among consumer printer developers and other 3D printing experts.

4.2.2.1 Current state of consumer 3D printing

In society, the interest in 3D printing has increased, especially when 3D printing became available for consumers. In the Netherlands there are a few consumer printer manufacturers active. These manufacturers also saw an increasing interest among society, because many people heard of this new technology. However, they have sensed that only some people saw the benefits of using a 3D printer. According to these developers most of the consumer printers are currently used by hobbyist, do it yourselfers and some educational institutions to equip laboratories for hands-on learning. The following quote illustrates that society mainly does not understand the use of 3D printing.

> *'There are people who have never heard of it, however now almost everybody heard of it, on the news or from kickstarter projects, only those people do not understand the benefits. For example, at parties, I always get the question 'what can I do with it?'. Those are the people who have heard of it and they also understand how it works, but they still think, 'yes, but so what, you can still buy stuff at Ikea?'.*
> *(Interviewee 12: Developer of consumer 3D printers)*

The makers movement, a current trend, is mentioned many times to address why 3D printing is popular among hobbyists or so-called 'Makers'. The two manufacturers of consumer printers and some other experts explained (Int. 5, 6, 7, 12, 14) that mostly hobbyist who like to make things on their own are very interested in 3D printing. A place that attracts these makers are the so called fablabs (short for fabrication labs). These fablabs contain all sorts of different manufacturing machines; the 3D printer is one of these tools. According to some participants (Int. 12, 13, 14), these fablabs help to make the use of a 3D printer bit by bit more common and accessible in society. The following quote explains the makers movement.

> *'That need-to-make-things-by-yourself and the feeling you get when you made something is what people are discovering and that describes the makers movement, so the making of your own designs and being proud of what you have made. Through this it becomes possible to do great inventions in your free time without spending much money '.*
> *(Interviewee 7: expert in marketing with 3D printing)*

Another driving force behind the developments in consumer 3D printing is the open source communication of designs. Many people share their 3D designs or inventions on internet communities where everybody has access. One consumer printer developer gave the example that people at home improved their printers and shared these improvements with this company, where after they adjusted their machines. Furthermore, it is possible to find all sorts of designs on the Internet which could be printed on your own printer or for instance in a fablab. According to many participants (Int. 1, 2, 3, 5, 7, 9, 12, 13, 14), this broad accessibility of designs is an important driver of the use of 3D printers.

4.2.2.2 Developments in consumer 3D printing

While consumer 3D printing is now popular among hobbyist, 3D printer developers have the ambition to make 3D printing accessible for everyone. However, before all people could have a printer at home, lots of technical development is needed in order to make the printers more 'consumer proof'. The developments in consumer 3D printing have a lot in common with the developments in industrial 3D printing. Most of the developments that were mentioned were technical in nature, because many interviewees (Int. 1, 2, 3, 5, 7, 10, 12, 13, 14) expected a large shift to consumer use when the 3D printer offers many more possibilities then it offers today and when it is more easy to use. Especially this last desire came up often, because nowadays printers are not consumer friendly, not plug-and-play as a television. The next decade most developments will take place in machine and material adjustments and enrichments. These desired developments reveal the desired future use of consumer 3D printing.

Within the consumer print industry there is a desire to expand the pallet of materials. Some participants (Int. 1, 2, 4, 5, 6, 9, 12, 14) explained that at this moment, the pallet of materials is still very limited. Most prints consist of plastic, other materials which could be printed are for example wood and rubber. The upcoming years many more material types will be developed. As in the case of industrial 3D printing in the first place attention will be devoted to the adaption of approved materials for classical fabrication techniques as injection molding. With some adjustments these types of materials might be possible to use for consumer 3D printing. Examples of new developed materials that are mentioned are different metals, such as copper.

According to the developers of consumer 3D printers, an important step to a more complete consumer 3D printer would be a multi material printer for personal use. Some of the participants (Int. 5, 6, 12, 14) have the vision of printing functional end products with a consumer 3D printer. However, as stated earlier, nowadays most consumer printers only print with one type of material, where most functional end products exist of more material types. The following quote exemplifies why a multimaterial printer could contribute to the societal adoption of consumer 3D printing.

> *'At this moment there are printers, like ours, which make things with plastic. However, in the future there will be printers, which use both glass and plastic and copper as print materials. Why are those three types important? Well, because when you take a close look to all the products around us, those exist roughly out of conductive materials, insulating materials and glass.' (Interviewee 12: developer of consumer 3D printers)*

To develop such a multi material printer the participants (Int. 5, 6, 9) expect that different 3D printing techniques might be merged. For metal printing most of the time different techniques are used then for plastic printing, for example SLS for metal printing and FDM for plastic printing. Though, a few (Int. 4, 10, 11) participants think it might be a challenge to make a multi material printer which is still consumer friendly. Firstly, because the temperature that could be reached by metal printing is much higher than with plastic printing. Secondly, people would possibly use material powders or other forms of material to print objects. The participants have their doubts about these type of materials and if they should be, proverbially, in everyone’s living room. Therefore, the opinions about multi material consumer printers are divided among the participants. Some have the ambition to make such a printer, others doubt if it is safe enough for consumer use. The following quote illustrates the type of reasoning that leads to the conclusion that people should not work with material powder at their homes.

> *'These are things (use of material powder with high density) that should take place in industrial environment, not at home. The filament with local heating, what happens there is manageable at home, that is also*

the reason why it became so popular. That coil with filament is not the problem. But that process with powders and stereolythography with monomers etc, that is not something suitable at home. ... you are doing chemistry' (Interviewee 4: expert in 3D print materials)

Another mentioned development is about the development of consumer friendly software. Some participants (Int. 1, 2, 10, 12, 13) explained that most of the current software is hard to understand for ordinary people. This is seen as a huge inhibitor for the transition of consumer 3D printers to the entire society. As long as ordinary people are not able to work with the software the participants expect that 3D printing would never be accepted by the whole society.

Notwithstanding that 3D printers may have more possibilities and are easier to operate in the future, according to all participants the biggest barrier probably still remains, which is resolution vs. speed. Printer developers want to produce printers that print with high speed, however, this goes at the expense of the quality. People probably want to print as cheap as possible, however, this goes at the expense of material properties. One of the participants summarized it as following:

'The most ultimate printer prints fast, cheap and very good, this will develop, however, it will develop stepwise.' (Interviewee 2: expert in design methods for 3D printing)

From the interviews it also appeared that there are initiatives to connect consumer 3D printing with recycling. A frequently heard development was recycling plastic to filament. This development is in an experimental phase and is only used on a small scale. Plastic was put in a shredder and subsequently melted to filament. However, the quality of these filaments is not the same as that of normal filaments, because the features changed much after heating. Yet many participants (Int. 1, 2, 5, 6, 10, 14) agreed that this development is valuable and desired to make it applicable on large scale. Two participants had the ambition to contribute to a circular economy, where recycling is a standard. The following quote is an example of such an ambition.

'Our ambition is to bring a circular economy. By means of this concept (recycling plastic into filament and print objects) it is possible to involve consumers, who are often forgotten, into the recycling process. At this moment there are almost no applications for old plastic …. We try to use the consumers, so what they deem as useless, we create something useful with it and also personalized, that's the idea. You can make anything with useless waste.'(Interviewee 5: 3D printing & circular economy)

4.2.2.3 Desired future use of consumer 3D printing

A few participants had the vision that in 2060 every household will have a 3D printer at home (Int. 1, 5, 6, 9, 12, 14). This vision was frequently described on the basis of the same example: when something in a household was broken, for instance a handle of a wardrobe, people could download the3D print design file from the Internet, print the product at home and replace it for the broken handle, instead of buying a handle in a store. This end product will be easy to make, because it exist from one material. However, these few participants expected that by the time of 2060 3D printers will be able to print different types of material which could make all sorts of functional end products, even recycle products and make new products out of it.

> *'When the technique is much developed and printing with high resolution is possible, it is possible to print fully functional models out of that one machine in once. So a whole lamp, completely with a functioning light bulb. When you take it, you plug it into the AC outlet and it works.' (Interviewee 12: Developer of consumer 3D printer)*

Yet, other participants (Int. 4, 8, 10, 11) did not had the vision of a 3D printer in every household by 2060. They did think it might be feasible, however not realistic. Besides, technical barriers that may be hard to overcome, they agreed that there are also some other aspects that might involve the future use of consumer 3D printing. One of those aspects is the business case of consumer 3D printing. The participants expect that this could be a big hurdle in the transition of 3D printing to the households. In the upcoming years the printers might have more advanced features, however, they doubt if these printers will be inexpensive to purchase. They doubt if it is profitable to sell these consumer 3D printers, especially multi material printers.

> *'The question is if it is profitable or is it anyway a business case to print with metal. How many times are we going to print something with metal?' (Interviewee 9: Expert in 3D printing technologies)*

> *'It is a professional technology (metal printing), so I do not see that it will soon take a shift towards the living room. The underlying technology is simply too expensive and it never will be any cheaper.' (Interviewee 8: developer of industrial 3D printer)*

Another influence, mentioned by some participants, which may have impact on the future use of consumer 3D printers, positive or negative, is the acceptance by the general public. Nowadays, consumers are depended on the industry for the manufacturing of goods. The industry tries to foresee the needs of the consumers and adapt to these needs as much as possible, however the industry is not able to fulfil all personal needs. When consumers make products themselves, they are no longer depended on the industry. Consequently, they can fulfil their own needs. Some participants (int. 1, 3, 5, 6, 12, 14) mentioned this new freedom of design as argument why the general public is willing to adapt the consumer printer. They sensed that the society is changing; people want to be more involved into the fabrication process and want more customized products. Consumer 3D printers could be a fabrication technique which fits this change. Other participants had their doubts about this change. These participants (Int. 7, 8, 9, 11) think that the current consumers are spoiled and not used to more involvement in fabrication processes. The threshold for consumers to design their own products might be too high. Therefore, a few participants expect that most consumers will not use consumer 3D printers in 2060 and still go to stores to buy their products.

'People are now more a passive consumer. We arrange our lives on the basis of things which are offered to us.' (Interviewee 6: expert in 3D printing & circular economy)

Furthermore, some participants (Int. 1, 2, 7, 10, 12, 13, 14) expect that schools will be important future users of consumer 3D printers. They think that within 5 years every high school should have a printer, because children should learn how to work with the software and the printers, because this technique seems to become a common technique in the industry. Therefore, some companies pleaded for the use of 3D printers at school. Subsequently, some participants expect that the consumer 3D printer market will grow when all schools have a printer. The following quote explains this statement.

'I am convinced that the consumer market will only grow when you start with 3D printing on schools…..The consumer market starts to grow when children start asking 'Could we have such a printer at home?'' (Interviewee 10: author of a book about the developments in 3D printing)

Another aspect, that was not necessarily desired by the participants, but was thought to have much influence on the success of consumer 3D printing is 3D scanning. When it becomes easier for a consumer to scan objects, they also might like to print these objects. People do not have to design products on the computer but only scan the objects they want. A few participants mentioned that in 2060 3D scanning is greatly developed and accessible for every consumer.

'Combine 3D scanners with 3D printers and you can remake every product… This will be very interesting I think.' (Interviewee 5: expert in 3D printing & circular economy)

4.2.2.4 Impact of consumer 3D printing

Assuming consumer 3D printing will develop the upcoming decades, it will have impact on sustainability, safety and society. In next paragraphs the envisioned impact on these aspects is described.

4.2.2.4.1 Impact on sustainability

All participants saw many positive effects of consumer 3D printing on the environment. According to all participants, when consumers will print their products at home, this will have much impact on the manufacturing industry. The industry will produce less products and subsequently has to transport less products around the world. Distribution of products will slowly shift to distribution of raw materials, which can be transported much more efficient. A possible effect would be that the carbon footprint of transport will decrease sufficiently.

A few participants (Int. 3, 7, 12, 13) expect that it is less likely that consumers throw away their products, because the products might be personalized, suit them better and are therefore more worth to consumers. However, one participant think this effect will not last long, because when all products are personalized, personalized products will no longer have a high added value. The following quote explains why the interviewees thinks that personalized products will be thrown away less easy.

> *'I think that people will have products that better suit them. You are no longer depended on what is mass-produced and therefore you put more value to the product and perhaps higher prices will be asked. Subsequently people throw less away, because it is personalized, phone cases are getting much more beautiful than those dull cases.' (Interviewee 7: expert in 3D printing and marketing)*

However, because consumers have more accessibility to production, some participants (Int. 5, 8, 10, 11) were worried about the waste of plastic. The demand for plastic becomes higher and nowadays people print most of the times only bauble and have no applications to recycle it. Therefore they think that the development of recycling should not be forgotten otherwise consumer 3D printing is less sustainable. The following quote exemplifies why recycling of waste must be considered in the development of 3D printing.

> *'I think that 3D printing will cause a revolution in circular thinking and acting. The unnecessarily use of finite raw materials, when you take circular thinking and acting to the future and into the developments, there is a risk that it will be forgotten. When it will be taken into the whole development of 3D printing than I would really love that!... for the first time in history as regards to plastics and non-perished materials, recycling comes back into the hands of the people.' (Interviewee 5: expert in 3D printing & circular economy)*

4.2.2.4.2 Impact on safety

The envisioned impact of safety could be divided into two types of safety, safety of the machine and materials and safety of the use of products created by a consumer 3D printer. In the first case, all participants did not see any safety issues for the use of a consumer 3D printer. Most of them mentioned that the use of a 3D printer is not more unsafe than other types of technologies. Some (Int. 3, 4, 12, 13, 14) were aware of the emission rates of nanoparticles, a few (Int. 3, 4) were concerned about it, but most participants thought that those rates were not alarmingly high. There were however questions about the use of some materials that might come on the market. Specific names of materials were not discussed, however what they (Int. 3, 4, 13) meant to say was that it is not desirable to put every material into a consumer printer. Some materials might be too dangerous for consumer use because of toxic vapors. The following quotes illustrates the visions which participants had on the safety of materials.

> *'When these printers come in all of the living rooms you have to make the printers a bit dummy proof. So then there must also be an extractor on it or something like that, there must come stickers for materials (do not use it for!), a cap should be placed over the nozzle.' (Interviewee 12: developer of consumer 3D printers)*

> *'Undoubtedly there will come materials of which I think it is unsafe to print with. However, the same could be said for goods that you could buy in the supermarket. About some products you could also say, is it*

clever to eat this every day, all those colorants, and additional flavors. When you think about it that way, well then I do not foresee any problems ' (Interviewee 8: developer of industrial 3D printer)

There were more concerns about the use of products made with a consumer 3D printer. A big concern has to do with the CE standard, which stands for Conformité Européenne. A manufacturer indicates with a CE mark that a product satisfies the European requirements in the area of safety, health and environment. Products which do not meet the requirements may not be sold. In the case of 3D printing and especially 3D printers for consumer use, the printed products are not tested to see if they meet the CE standards and regulations. Most participants (Int. 1, 2, 3, 5, 7, 11, 12, 14) realized that when consumers print their own products, it is not guaranteed that those products are safe to use. This holds especially when the features of the materials after printing are not fully known yet. This was seen as a risk, though some thought that no accidents will happen. A question related to this risk concerns the liability when something goes wrong. It is not clear who can be held responsible; will it be the manufacturer of the printer, the consumer who printed the product, the material manufacturer, the designer? Some interviewees thought it will be hard to find a solution for this problem. The following quotes illustrates the concerns that they have about the CE standard.

'The CE standard is adapted on the old model, on the model of the multinationals with product development departments with hundreds of people, where products are developed and where thousands of euro's are spend to test if the product is safe and subsequently CE certify the product. Well, this is suitable for mass produced objects, but how does it work with unique objects? Objects that are made by the consumer?' (Interviewee 7: expert in 3D printing & marketing)

'Later it (CE standard) will all turn around, because than we don't have any control. Than it is the responsibility of the citizen or is it the responsibility of the government? Because they are responsible for the CE standard, however, at the moment that I, as cocky as I am, going to print my own stuff than no one could control it.' (Interviewee 5: expert in 3D printing & circular economy)

4.2.2.4.3 Impact on society

On account of consumer 3D printing, a large impact is that manufacturing technology becomes more accessible to consumers, which will have several effects on the society. For instance, all interviewees mentioned many times that consumers get enhanced possibilities to express their creativity. With 3D printing consumers can print their own designs and translate their ideas into physical objects. This technology therefore is likely to have a great impact on the world of art. Furthermore, it was mentioned (Int. 3, 5, 12, 14) that taking the step towards becoming being an entrepreneur becomes more easy. Normally, when people had an idea for a product, they had to invest much money to produce it or make a prototype. With 3D printing this costly process of prototype making becomes within reach of most of the consumers. Some participants (Int. 3, 5, 6, 7) call this the democratization of technology; everybody in the society will have access to manufacturing technology. One participant summarized the impact on society as following:

> *'It is all about democratization of technology, which means it becomes accessible for everyone. It is not only accessible for multinationals, but it also becomes accessible for everybody.' (Interviewee 7: expert in 3D printing & marketing)*

Another small impact mentioned by some participants (Int. 5, 6, 10) is that the society might become a little bit more personal and open. For example, people could give personalized presents or share self-made designs. Thereby, online communities arise where people share designs with each other.

There is a flipside of the openness of society and the sharing of designs however. An issue that came up frequently is about intellectual property. When creations of designers get on the internet for free and people print them, it may have major impact on the industry and designers, because they will not be paid for their designs. In the extreme, consumers could print whole products and only pay for the material, where normally these types of products costs many more. The reactions about this issue were divers. Some participants (Int. 1, 2, 6, 10) see it as a possible danger and want the government to make a statement about it. Others (Int. 3, 4, 8) think that consumers are never able to print an equally good product, because the consumer printers never reach the quality of industrial printers. Others (Int. 5, 7, 12, 14) think that the industry should adapt to it, for example putting the designs online, people have to pay for does designs which could only be printed in certain shops. This last future vision should have the condition that those designs do not come for free on the internet. The following quote illustrates how easy it could be to download designs form internet.

> *'Making a design on your own for a part of your vacuum cleaner is a bit hard. However, you don't have to do it, because most of the time you could download it from a website like Thinkiverse or in the future from the website of Miele for example. However in the case that download from a site and there is an intellectual property, yes, then suddenly there is something changed from how it was before.' (Interviewee 5: expert in 3D printing & circular economy)*

In Figure 4.3, at the next page, the main results from the interviews with consumer print experts are presented. The exclamation mark indicates the subjects that need attention. The no entry sign indicates the subjects that currently hampering further development of 3D printing in the consumer domain.

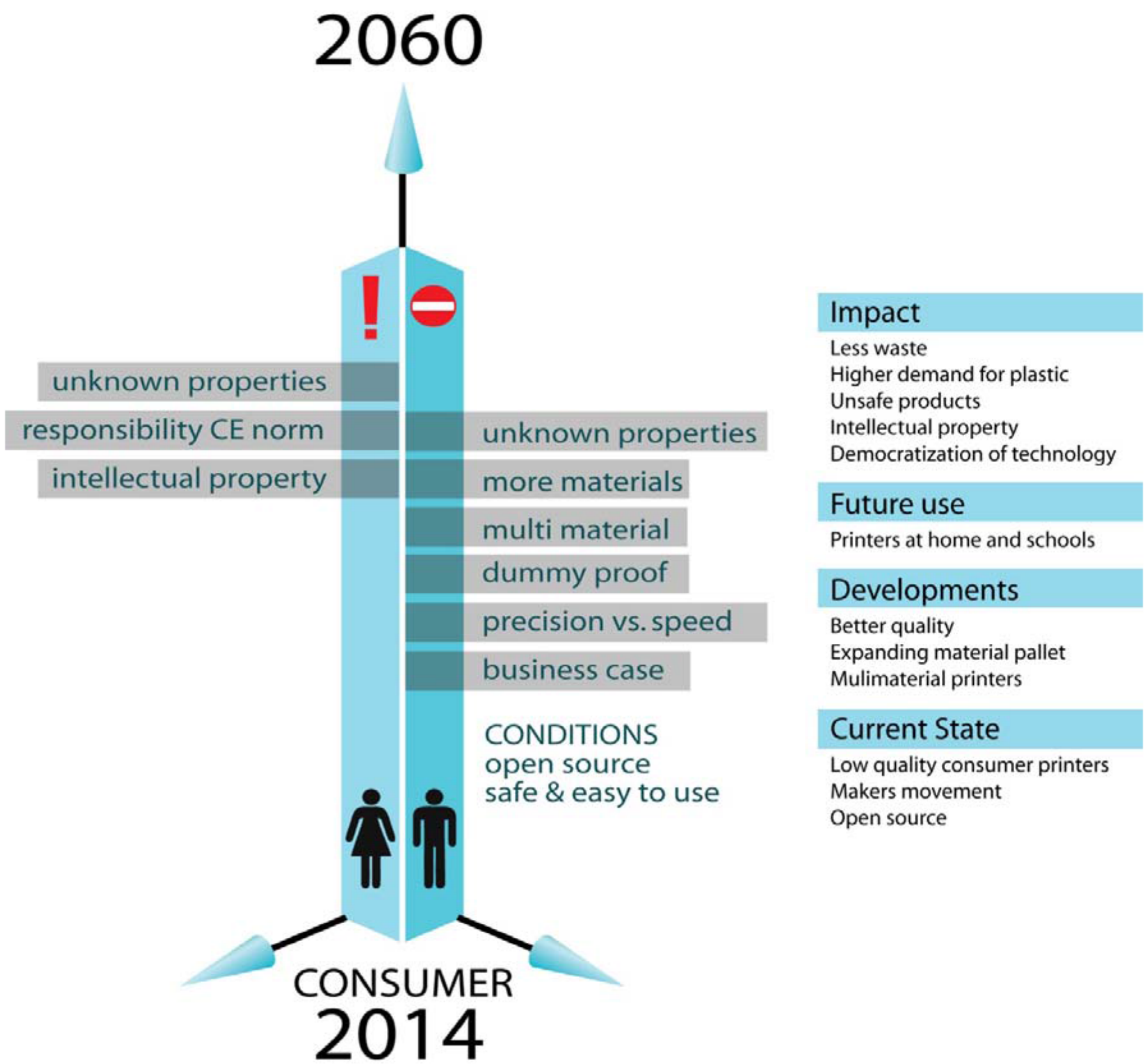

Figure 4.3: Summary of the results from the consumer domain

4.2.3 Food

The future of 3D printing which is the most uncertain is the one of 3D food printing. In this area a lot of research questions have to be answered before it will be possible to provide an evidence based view on what the future will look like. The guiding visions described below will give a good insight into the desired developments and desired future, according to food printing developers.

4.2.3.1 Current state of food printing

Food printing is an area that is still in its infancy and even most participants from the other domains think it is an enormous hype . At this moment, there are only a few food printing applications. One of the applications which was mentioned by the participants (Int. 10, 13, 15, 16) is the development of consumer foodprinters. This printer print could print chocolate, different dough and lots of others pureed ingredients. However, most interviewees think that the possibilities of this printer are still very limited. For example it cannot print a 'ready to eat' pizza crust, as after the dough has been deposited in the right way by a 3D printer, the dough still has to bake in a traditional oven. Besides chocolate, it does not produce 'ready to eat' food. Therefore, one participant (Int. 13) doubts whether the technique could be called food printing or that it just is a computer-controlled piping bag. Nevertheless, according to two participants (Int. 15, 16) restaurants are enthusiastic about the possibilities of these types of food printers. The following quote illustrates the reactions on food printing of interviewees from other domains.

> *'I don't see the advantages of food printing, it is overestimated, people think with food printing that you are doing some mystical things at the top and then there comes a cauliflower out of it, of course it does not work like that!... Food printing is just an enormous hype.' (Interviewee 13: director of a fablab)*

In the Netherlands, a few companies work on 3D food printing. At this moment, these companies only do research on food printing or plan to do research on it. According to one of the interviewees (Int. 15), 3D food printing can be defined as 'a device that can produce any kind of food product starting from series of basic ingredients using printing and other deposition technologies.' Both companies that were interviewed agreed that food printing is still in its infancy and only processed foods are used to print with. However, both had the ambition to bring food printing to a higher level were food printers will be a common device that might print complete meals. The following quote illustrates the current state of food printing.

> *'At this moment we are only working with processed foods, thus no food which you could get directly out of nature, so no broccoli or salad, but for example pasta and chocolate.' (Interviewee 16: expert in food printing)*

The two foot print developers had several reasons why food printing should be developed. Firstly, it was mentioned that with 3D food printing, people do not have to be very good cooks in order to make varied and good meals. People could download varied recipes from internet and upload them on their printer. Secondly, which is related to the previous, is that it might be possible to print personalized food. Depending on age, gender and health status, the recipe will be adapted and therefore might improve people's health. Thirdly, food printing may enable the creation of new food. For example food with algae components or protein from insects (e.g. grasshoppers) which looks attractive enough to eat. Finally, new textures or flavors could be created. These reasons already give away some of the developments that are described in paragraphs that follow.

4.2.3.2 Developments in food printing

Most developments in 3D food printing are still in a very early phase: experiments are set up in order to examine what it is possible and what applications could be developed. One of the big questions the interviewed researchers deal with is which 3D print technology could be used for food printing? Most 3D print technologies are used for other types of applications, not relating to food, therefore it is uncertain whether these technologies could be used for food applications. Both experts experimented with FDM and SLS and both technologies seemed to be applicable for printing food. However, especially with SLS the question is how the laser affects the food. The following quote explains why.

> *'With SLS you also bring heat in it (food) and that might burn for a part, what happens there? … With the use of a laser, you could question if it is healthy. You have to draw the line somewhere and that should be explored.' (Interviewee 15: expert in food printing)*

Another question which the participants explore is about which food could be printed and which food not. A related question is about the scale of printing. What is the minimum size of a print job? Would it for example be possible to print proteins? While in other areas developments are slowly progressing towards printing multimaterial, in food printing this is one of the most relevant challenges. Food is a very complex multimaterial; there are different structures, different contrast, different flavors and nutrients. In the upcoming years, researchers will try to find answers to these types of questions. Research on printing structure will take place. Furthermore, there might be examined if it is possible to approximate food, creating food, which looks and taste normal, but in fact contain different ingredients. The following quote explains why food is such a complex material.

> *'The complexity of food is really high, when you take a look at the printing of materials, plastics or something like that, there the structure of the materials is relatively easy, metal melt together and plastic melt together and that's it. While printing a bread is very complex, because there are lots of different structures in one bread, and in some places you would have more starch and in another peace more proteins. The complexity is really high and where is the limit and on what scale could we print?' (Interviewee 15: expert in food printing)*

One development mentioned by the interviewee (Int. 15), which was seen as meaningful also by other interviewees, was food printing for elderly people in nursing homes. Normally, elderly people with chewing and swallowing problems eat pureed food. However, this type of food is often not perceived as very attractive by this group of people In practice this can lead to malnutrition and subsequently to health problems. One of the companies which was interviewed worked on a project to print puree back into the natural form, for example carrot puree was printed into the form of a carrot. A thickener was added in order to prevent the printed puree for sagging in, yet the soft structure remains. In this way, the meals looked more natural and therefore the elderly people might regain their appetite. Furthermore, there was the ambition to make the meals personalized by adding vitamins or extra fat etc., depending on the needs of the patient. The following quote explains the project.

> *'Carrots are cooked and pureed, and then there is some extra oil added. Those people have smaller meals, however they have to take up enough nutrients, so you add some extra oil, some extra calcium etc. In this way you ensure that there are printed meals, which are: 1. More attractive than puree and; 2. personalized. Personalized is very important because it ensures a better health and that is with the current technologies not easy to do.' (Interviewee 15: expert in food printing)*

4.2.3.3 Desired future use of food printing

Eventually, when food printing is well enough developed, the two participants expect that the first food printers will end up in the food industry before it will be available for consumers. The industrial food printers might be less advanced than consumer food printers. One interviewee gave the example of a big industrial chocolate printer that could print many customized chocolates at once; this printer may be much less advanced than consumer printers. Consumer food printers should print different types of food and may therefore be more complex and need more time to develop. The interviewees expect that these consumer printers are firstly used by restaurants and other cooks and eventually ooze out to the rest of society. The following quote describes the expected development of food printing.

> *'Well, first some professional cooks start to work with food printing, after that some small high tech companies will come on the market or purchase on the internet. Then there will come a network of some of those small companies which will work together virtual. Parallel to it some innovators, like me, will also take such a printer in house.' (interviewee 16: expert in food printing)*

Both food printing developers desired that every household has a food printer by the time of 2060. They think it could be possible that food printing would be a common technique in the kitchen, just as other technologies like a microwave. Cartridges with all sorts of ingredients or compound of ingredients could be placed at the top of the printer. These printers should produce a variety of meals; otherwise, the food printer might not get on the consumer market. One food printer developer even thinks that within 5 or 10 years 1 to 5% of the Dutch society will have a food printer at home. The following quote illustrates their point of view.

> *'When by 2060 it still isn't possible to have those printers at home, it never will be a success, so it would be possible to have a printer at home and this printer should produce a variety of food. Otherwise, it doesn't deserve his place in the kitchen, than it is just like a bread maker which only makes bread, and after a year it is put in the loft.'(Interviewee 15: expert in food printing)*

Furthermore, the interviewees desired that printed meals where personalized and therefore healthier for consumers. Extra proteins that could be added do not have to come from animals, but algae or other substitute proteins. Maybe even new foods with new flavors and structures could be made from algae's or for instance grasshoppers, these contain many proteins, but are not very popular among consumers because of their unattractive appearance. With the food print technology new shapes could be given to these algae or grasshopper meals, which could make it more attractive.

The participants, however, realized that the success rate of food printing may depend on other factors which show many similarities with the influencing factors of consumer 3D printing. One expert doubted about the business case of consumer food printing. It could be questioned whether it is useful to print everything. Why printing a broccoli when it could be bought in a supermarket for probably less money? The next quote explains why it is not efficient to print everything.

> *'You should not print everything, some things are best done with the current technology or with the classical methods of growing plants in greenhouses; we are good in that. You have to know exactly what the added value of food printing is.' (Interviewee 16: expert in food printing)*

Another factor, which the participants think may have a big influence on the success of food printing, is the acceptation of society toward food printing. Food is something that is close to the people and therefore society might be reserved toward printed foods and therefore might not use consumer food printers or buy printed food. Presumably, the resistance towards printed food depends on the type of food. Processed foods nowadays might be perceived as 'unnatural' and therefore it might not be a problem when it would be printed. However, natural food which is printed might than be seen as unnatural and therefore not desired by society. The next quote exemplifies the possible reactions of society on printed food.

> *'When something comes out of a press or a normal 3D printer, nobody cares. Chocolate from a printer, everybody finds it exiting and eat it. However, when I will print a beef, than the same happens as with the cultured beef, than people are going to say 'wait a minute, beef should come from a cow.' With chocolate, nobody cares, because it doesn't grow on a tree.' (Interviewee 16: expert in food printing)*

However, the other participant also thinks that society is willing to use technologies that are useful for them. He sees consumers as people who are waiting for things that are better and cheaper, when things got more convenient society will use it. Therefore, when food printing becomes more convenient than cooking it might be possible that consumer fully accept food printing. The following quote illustrates why people could accept food printing.

> *'We live in a high tech environment and what is possible will happen. We don't need a color television, we don't need prepackaged vegetables, we also don't need ready-to-eat meals, and still it is there. It all goes on, and it will go on, because what is possible will happen.' (Interviewee 16: expert in food printing)*

4.2.3.4 Impact of food printing

Assuming that food printing will develop as desired by the developers and food printing becomes a common technology, the participants envisioned some possible effects on sustainability, safety and society. In the next paragraphs the impact on the three studied aspects are outlined.

4.2.3.4.1 Impact on sustainability

Two possible positive effects of food printing on sustainability were mentioned during the interviews. Every year many food is thrown away before it reaches the consumer. In many cases, rotten food as vegetables and fruits is thrown away, however also misshaped food often does not reach the shelves in the supermarkets. This latest category, although misshaped, is fine to eat. Both participants think that food printing could make use of this waste stream. For example, in the case of printing purees it does not matter what type of shape the pureed vegetables have. Therefore, this waste flow could decrease.

Another possible effect that was mentioned is lowering the carbon footprint by using substitute proteins. If it will be possible to print meat substitutes that have the interest of the whole society, less meat will be produced. Cattle breeding has high emissions of carbon, therefore when less cattle breeding is needed it may decrease the carbon percentage in the air.

4.2.3.4.2 Impact on safety

As earlier mentioned one participant investigates if the use of a print technologies with lasers is safe enough for food applications. Next to this research question, no other safety issues where mentioned. The participants mentioned that new ingredients or new unqualified compounds could be added, however they think when the qualification process went following protocol and regulations no safety problems will occur.

> *'Our food has never been safer before. The systems, hygiene designs and the risk analyses that we conduct, quick screening and al that kind of stuff is better than ever.' (Interviewee 16: expert in 3D printing)*

4.2.3.4.3 Impact on society

Both participants envisioned that food printing could have a great contribution in costs reductions in the healthcare. When it is possible to print personalized food, people are able to eat food that is adapted to their health status, especially, people with a special diet as for instance pregnant mothers who need some extra vitamins. With personalized meals, diseases related to sub optimal food intake are less likely to occur. Another effect that might occur is that people will cook less on the traditional way, whether this is positive or negative is not mentioned by the experts.

At the next page the main results from the interviews with food printing experts are presented (Figure 4.4). The exclamation mark indicates the subjects that need attention. The no entry sign indicates the subjects that currently hampering further development of 3D printing.

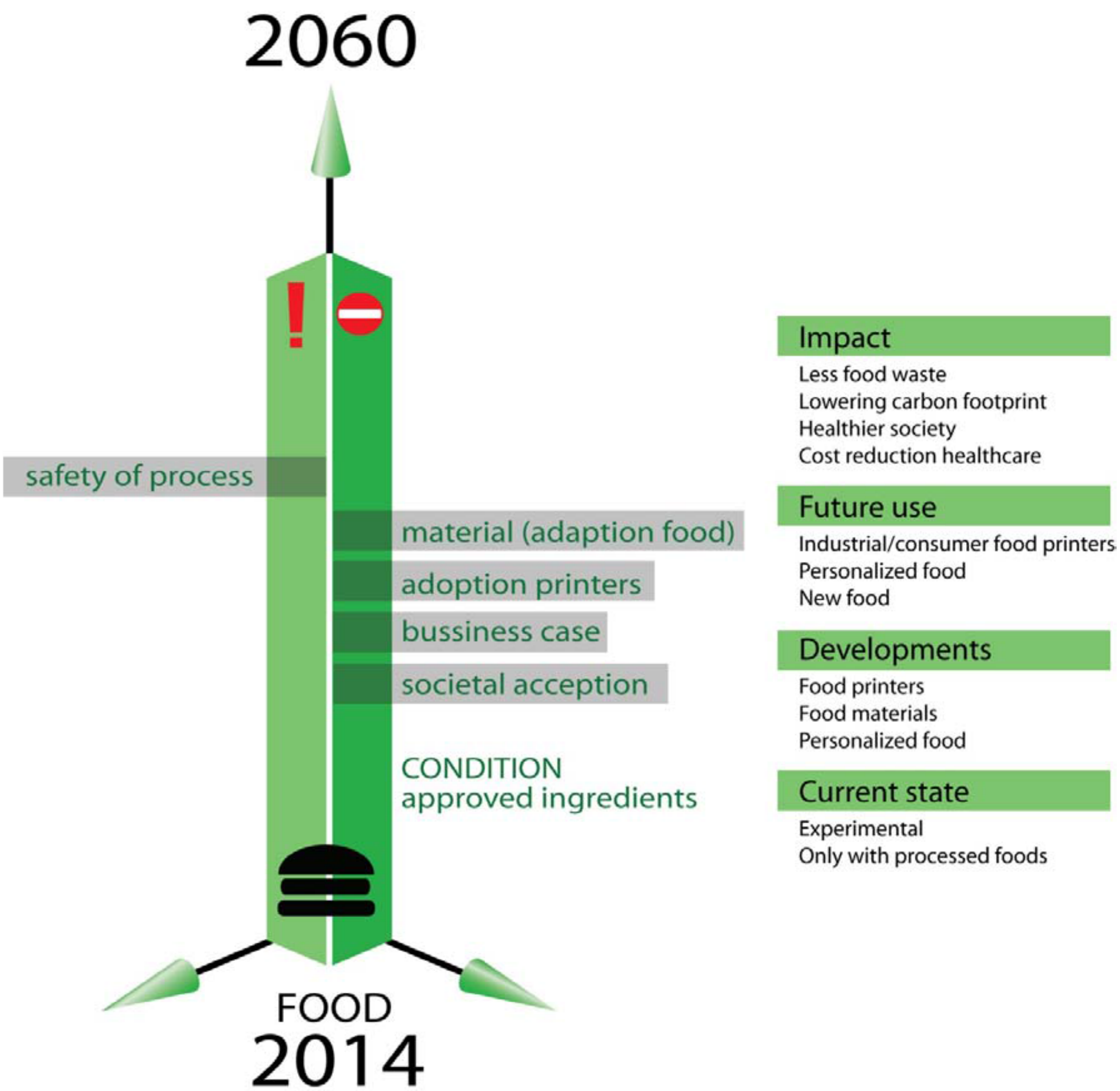

Figure 4.4: Summary of the results from the food printing domain

4.2.4 *Healthcare*

One of the most promising domains in the 3D printed market is healthcare printing. According to the desk study this domain could be separated into two specializations. The first is medical printing, which refers to printing of prosthetics and medical helping devices. The second is bio printing, which refers to tissue engineering or regenerative medicine. In this paragraph, the current state of bio printing is outlined and the future developments and desires are described.

4.2.4.1 Current state of healthcare printing

Among all participants of the qualitative study healthcare printing was seen as the most valuable application of 3D printing, because it can have a large impact on the quality of life. Medical 3D printing, one the two specializations of 3D printing in healthcare, is used to print patient specific implants and devices for medical use; this branch of healthcare printing is already highly developed. Several applications mentioned by the interviewees are outlined in the next paragraphs.

The interviewees in the health care 3D printing applications domain (Int. 17, 18, 19) explained that due to the advantage of freedom of design, it is possible to customize different medical devices. For example, it is possible to custom prosthetic designs. The prosthetics can be adapted to unique anatomy of the patient's body, which even could lead to less recovery time. Furthermore, 3D printing offers great possibilities for surgery planning. The anatomical models that are 3D printed are made for a specific patient using data from different medical- imaging technologies, like MRI. In the case of complex surgeries these physical replicas of a patient's bone structure or soft tissue are helpful to determine the best courses of action for treatment and procedures. For example, surgeons are able to decide in advance the place of the incision. Thereby, due to the pre-printed model, the surgeon is able to practice in advance, which can make the operation more efficient. Another application of medical 3D printing is virtual surgery planning and personalized surgical instruments. In advance of an operation personalized instruments could be designed which could be used as a guide during the operation. By using these instruments the three experts expect that the surgeon and the other members of the medical team can provide their services better and more efficient, which will benefit the patient. The following quote summarizes the different applications of medical 3D printing.

> *'The most simple application of 3D printing is using it for prototypes. You can print skulls with a fracture and practice on it; thereby surgeons are able to plan their operation in advance. That is the simplest application. Step 2 is, using inter-operative devices, like; saw moulds that are patient specific. On the base of MRI scans, you can make these devices. Such a saw mould perfectly fits, for example, on the patient's knee, than you can also make holes in the patient's knee, just like an orthopaedic surgeon. Less expertise is needed and experience of the surgeon is valued less. Step 3 is implants. You may have heard about the scull that was implanted here in the hospital? Well, these are applications that are already being used, however on a small scale.'(Interviewee 18: expert in 3D printing and health care applications)*

The other application of healthcare 3D printing, bio printing, is according to the interviewees still in the experimental phase. The interviewees explained that 3D printing made it possible to print certain bio inks in a 3D structure, which are called scaffolds. Those structures could finally result into functional tissue with patient's own cells. Subsequently, this tissue could replace damaged tissue. Furthermore, this tissue could be used for research, like using it to test the effects of a certain drug. Currently, there are little to none applications available for society or other research. Only one example was mentioned by the experts, they all referred to the study of Atala (2011) who printed functional bladders and implanted them. However, what is not said in the literature but is told by the interviewees is that those printed bladders were already removed from the patients due to implications. The following quote illustrates the benefit of using printing tissues in research.

> *'We already know that responses from cells in a 3D structure are more in line with the natural responses then the responses of cells in a 2D structure.' (Interviewee 19: expert in 3D printing and health care applications)*

4.2.4.2 Developments in healthcare printing

During the interviews, healthcare printing researchers articulated many developments that are required for a desired future use of this type of 3D printing. Yet they expect that the desired developments will take longer than in other domains, because the applications mostly involve humans and therefore caution is needed. Researchers face many challenges, especially in the field of tissue engineering. Therefore, most developments take place in this particular domain of healthcare printing.

There are many different 3D print technologies on the market; however, these technologies are not all suitable for bio printing. The researchers elucidate that the temperatures that are reached with those technologies are too high and therefore lethal for the cells, in addition the obtained resolution is too little. Hence, special bio printers came on the market. However, these bio printers also have their limitations; due to the high resolution, these printers are very slow. For the future, the interviewees expect that these printers will be improved and more advanced in order to increase the quality and speed.

As in the other domains of 3D printing, developments take place to expand the pallet of materials. However, in tissue engineering applications one speaks of ink instead of material. According to the interviewees these bio inks should meet certain requirements. The inks should be strong enough to maintain their 3D structure, the inks should contain compounds that feed the cells and let them develop and the inks should be biodegradable and resolve when the cells are attached. At this moment there are just a few bio inks which meet these requirements, therefore some participants (Int. 17, 18) had the ambition to create more and also better bio inks. The following quote illustrates the importance of good bio ink.

> *'It is very important to find the right materials. An ink that is printable, in which cells are able to survive and the cells must be able to develop into the tissue what it should become.' (Interviewee 17: expert in 3D printing and health care applications)*

Remarkably, the largest developments in this domain did not relate to 3D printing, but to the processes around 3D printing. These developments should provide answers to questions like: how to extract enough cells out of the patients and how to cultivate these cells, how do cells behave after they are printed, how to let the cells adhere? In the next few years a collaboration is expected by the researchers between material scientists, physicists, molecular and cell biologists, chemists, and orthopedic surgeons to achieve the purpose to print functional tissues and use it for transplantation of tissue. The following quote contains the goal of one of the interviewed researchers.

> *'Personally, my goal is to use the printed tissues for transplantation setting, printing an entire hart or organ. I think it will not happen soon.' (Interviewee 18: expert in 3D printing and health care applications)*

Furthermore, in the field of medical 3D printing developments take place to increase the quality and reliability of the software. One researcher (Int. 17) explained that MRI scans are converted into a 3D model, which subsequently is printed. However, many times these personalized prostheses or molds did not fit. This happens because during the process of converting a MRI scan to a 3D model too much information gets lost. Better software could overcome this barrier.

Another desired development was to make so-called hybrid implants. These implants consist partly out of nonautologous material as titanium and are capsuled in autologous cells. These hybrid implants could coalesce with surrounding tissues in the body.

4.2.4.3 Future use of health care printing

The researchers in the field of bio printing and medical printing expect that by the time of 2060 3D printing will be a common device that is used for many healthcare applications. The earlier described current state and developments already gave away most of the desired applications.

While nowadays medical printing is only used for very complex cases, the interviewees desired that this technology becomes available for more patients. For instance they mentioned that operational planning is expected to be a normal preparation exercise among all surgeries even so the custom surgical instruments are expected to be common. However, they also expect in the upcoming years an certain amount of resistance form the surgeons, because the surgeons are not trained to work with these helping devices. Therefore, the participants plea that the current surgeons in training must practice with these 3D printed devices in order to let them get used to the technique of the future.

Furthermore, it was desired among the experts and participants from other domains that custom prosthetics become more available for society by 2060, even hybrid prosthetics. Yet they doubt if all the implanted prosthetics would be printed. One of the participants (Int. 17) thinks that also in the future only in the case of complex fractures will be chosen for a 3D printed prosthetic. According to this researcher it depends on three conditions if is chosen for a 3D printed prosthetic, the kind of patient, the capacity and the costs. For example, because it is expected that a child, who needs a new hip, would live longer when compared to an very old lady, this child may get a personalized hip while the old lady may get a 'normal' hip. This is exemplified in the following quote.

> *'When you have got a very complex leg fracture, for those cases it is interesting. In that sense it will not become very important for all of the patients, but it is quite a substantial improvement for complex cases.' (Interviewee 17: expert in 3D printing and health care applications)*

By 2060 the participants also expected that healtcare printing has taken big steps. By then it will be possible to print different functional and living tissue. This tissue will be used for all sorts of different applications. First, to replace for example cartilage in someone's knee. Because cells from the patient could be used, the chance on rejection of the implanted tissue is reduced. This may also apply for printed organs. Nevertheless, the participants did not expect that by the time of 2060 organs would be printed, because it is to complex. Second, the participants expect and desire to use tissue models for testing and screening of drugs and diseases. The tissue models could be used as an extra step in the clinical trial of medicines. Before drugs are tested on animals it could be tested on the tissue. The interviewees did not expect that animal testing would completely be replaced by tissue models, nevertheless this extra step will lead to less animal use.

4.2.4.4 The effects of healthcare printing

The changes that 3D printing trigger in the healthcare domain may have impact on safety and society. The sustainability aspect is omitted here because the participants could not identify significant effects on the environment or sustainability. In the following paragraphs the thoughts of the participants about the impact on the other two aspects are described.

4.2.4.4.1 Impact on safety

The interviewees did not formulate specific safety issues. They all mentioned an earlier described problem about the unknown properties or qualities of the objects after they are printed. In the case of printed prosthetics this could be seen as a serious problem, because the prosthetics should last for a while. Yet the interviewed researchers do not see it as a big problem and they think that when the technology advances, this problem is no longer an issue. Thereby, they mentioned that the current implanted prosthetics are tested on their strength before they are implanted.

4.2.4.4.2 Impact on society

The participants foresee some positive impacts of healthcare 3D printing on society, because it will improve the healthcare quality. First, due to the ability of customization of prosthetics, patients get better and customized healthcare. The chances on complications after operation might reduce, and even in very complex cases 3D printing could offer healthcare which was not able before. Second, the printed medical devices might lead to better and efficient operations. Surgeons could practice and plan in advance and during the operation they could use customized helping devices. Operation therefore may take less time, which is also in advantage of the patient, because it cost less money. Third, tissue engineering opens up completely new possibilities. While normally it was difficult or even not possible to replace damaged tissue it will become possible to repair certain tissues. It even could be possible that the damaged tissue is replaced, instead of an entire organ. Therefore, the waiting lists for donor organs might decrease.

At the next page an overview of the main results of the qualitative study for the health domain are presented (Figure 4.5). The exclamation mark contains the subjects that need attention. The no entry sign covers the subjects that currently hampering further development of 3D printing in health care.

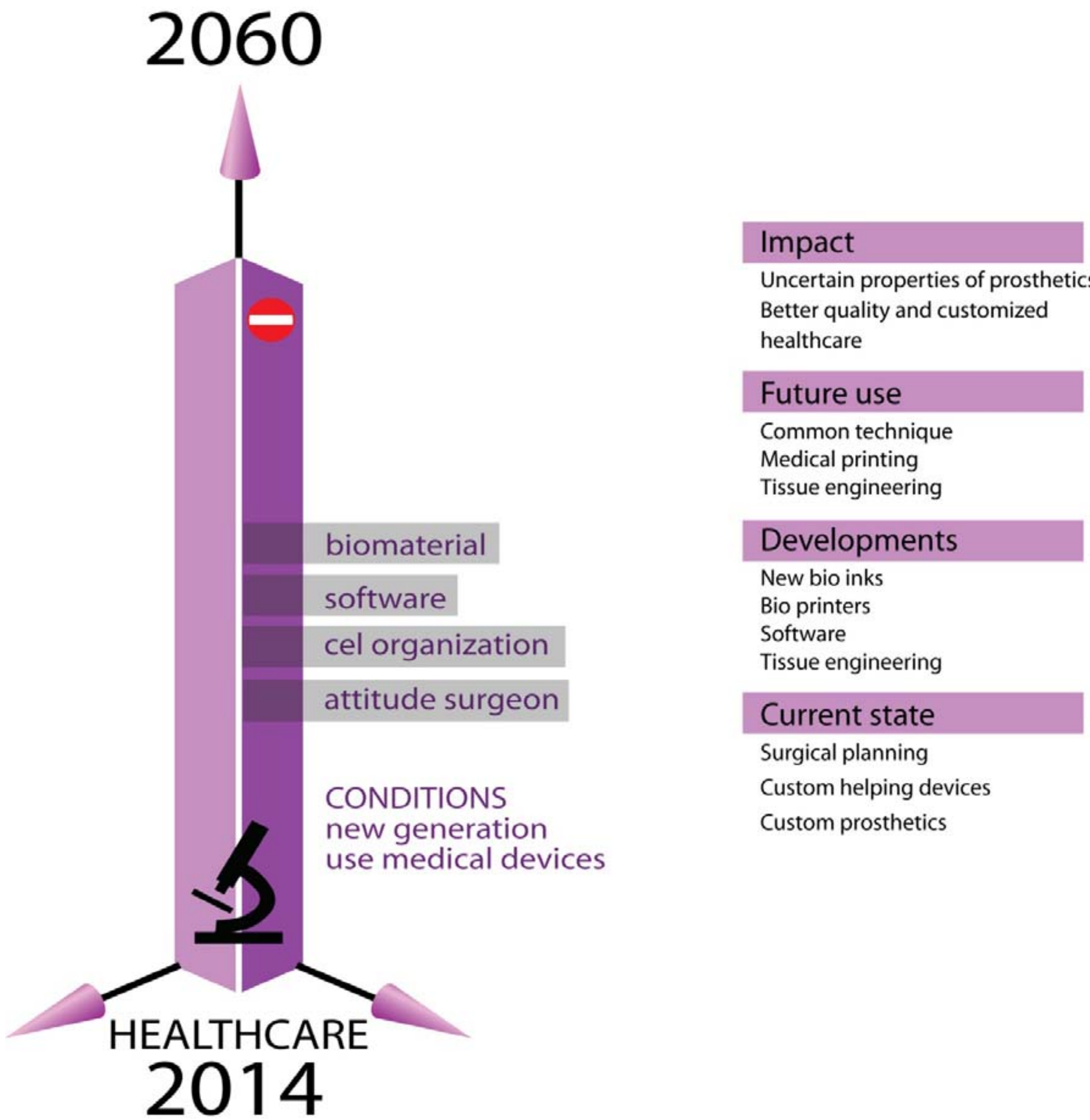

Figure 4.5: Summary of the results from the health care domain.

5 Discussion

The aim of this study was to explore the future development of 3D printing and its impact on sustainability/environment, society and safety. In the introduction of this research report, it is stated that these guiding visions are required to identify potential positive and negative impacts of 3D print technologies and to orient on future actions. In the next chapter the visions found will be presented in terms of our theoretical framework. In this chapter, some discussion on the results and recommendations for RIVM are provided.

5.1 Discussion of the results

5.1.1 Will 3D printing replace mass production?

Between the overlapping parts of the desk and the qualitative study there are generally no differences, yet there is one point were the two studies differed. Contrary to the expectations, which were formed on the basis of the desk study, the interviewees did not envision that 3D printing would substitute mass production. As described in the introduction in some literature 3D printing was seen as the new industrial revolution (Berman, 2012; Birtchnell et al., 2013; Huang et al., 2013;), however according to the results from this study this industrial revolution may not be as revolutionary as it was stated. Many participants foresaw that 3D printing will develop towards a common used manufacturing technique, but always placed this in a wider context where 3D printing has to compete with other manufacturing technologies. They thought that 3D printing will only be used for the production of small series and highly customized and personalized products. Here, designers and fabricators have more freedom of design and may therefore be more flexible in their production process. Nonetheless, the participants expect that mass production will still be produced with other manufacturing technologies. These findings are consistent with those of Wohlers Rapport (2014) who stated that 3D printing only has an added value in the manufacturing industry when it is used for the production of small series and highly customized and personalized products. The percentage of production lines, that meet these criteria and therefore are interesting to acquire by 3D printing, will say something about the extent of the impact that 3D printing might have. Production lines which do not meet these criteria might still use conventional techniques. Therefore, the findings of this study suggest that 3D printing is developing towards a manufacturing technology, but most likely will not substitute mass production as is stated in other literature and media.

5.1.2 Different ideas of the relevance of 3D consumer printing

Another interesting discussion point is about the different opinions regarding the future use of consumer 3D printing. Not surprisingly the consumer print experts are very enthusiastic about this type of technology and envisioned that every household has a 3D printer by the time of 2060. In contrast, most industrial 3D printing experts are not that enthusiastic and very critical about the future use of consumer printers. They do not think it will become a common device, because the technique becomes, due to the desired developments, more expansive and therefore less attractive for consumers.

There are several reasons why these experts differ in opinions. A first possible reason for this difference is that it is always much easier to be critical about a 3D printing domain which you are not personally involved with. Secondly, in the domain of consumer 3D printing the positive spirit of the maker movement attracts people with a strong belief in the possibilities of science and technology. These strong beliefs might explain a part of the differences. Although, in the industrial 3D printing domain the belief in science and technology is likely to be strong either. Thirdly, different perspectives on the question 'how extensive should be the use of consumer 3D printers to call it a success' might be a reason why industrial experts are more sceptical. For individual enterprises in 3D consumer printing it will be a success if they can make a good living with the purchase of 3D printers. For the industrial application of 3D printing a large share of 3D printing in industrial manufacturing processes will express whether it is a success or not. A fourth and possibly the most likely explanation for these differences in visions, is the state of the domains in the Gartner Hype Cycle (2014). As described in the results of the desk study, this hype cycle evaluates emerging technologies and trends by their degree of 'maturity' and to what extent the market and the public accept the technology. At this moment consumer 3D printing is evaluated as 'hype'. This is often accompanied with bold visions and great expectations. In contrast, the industrial domain is evaluated by Gartner as 'almost mature' this domain is already over the hype phase, experienced the drawbacks of the technology and sharpened their visions to realistic aims. It might therefore be that industrial 3D printing experts are more critical towards the future use of consumer printers. They might be aloof for bold statements and a bit more restrained in their expectations by experience. In general it could be said that consumer 3D printing will become mature, however in what extend it will be used remains the question, time will tell.

5.1.3 Different ideas about animal replacement by tissue engineering

In an earlier study, the RIVM examined the possibility to substitute animal testing by 3D printed tissue and concluded that it might be possible to fully replace animal testing (RIVM, 2013). Our study complemented these findings and put them in perspective. In our study researchers also mentioned the possibilities to replace animal testing with printed tissues, though with the caveat that complete replacement of animal testing is not possible. A clear explanation for these differences is not found. Although, the RIVM did not name a time frame in which it is possible to fully replace animal testing by printed tissue, our interviewees provided a vision of 2060. It may be possible that in the distant future, fully replacement of animal testing is possible, however for the upcoming decennia's it is expected that 3D printing only replaces animal testing for a part.

5.1.4 Reflection on CTA and Vision Assessment

We are confident that the approach of including stakeholders in the risk management process by means of a Constructive Technology Assessment (CTA) is a viable one. In fact it provides a clear roadmap for action, which is unfortunately less clear in the IRGC risk governance model (Renn, 2008), which provides the broader framework of the CTA in this study. The combination of the IRGC model with CTA combines the theoretical strands namely risk analysis and society and technology studies. The academic disciplines are unfortunately loosely connected , but we think that combining these perspectives is very fruitful.

We used the theory of Vision Assessment to collect visions about the developments of 3D printing in order to be able to manage 3D printing towards a desirable direction. The results of this research illustrate that the theory of Vision Assessment is an appropriate tool to make implicit guiding visions explicit. Besides guiding visions, this research identified concerns that need to be overcome and potential implications of 3D printing. Moreover, the results illustrate which aspects need further exploration and which follow-up activities must be performed in order to develop 3D printing in more desirable directions.

The four concepts of the conceptual framework supported to make the guiding visions explicit. They served as a framework to make guiding visions more clear and understandable. The interviewees extensively articulated the current state of technology. This provided insight in which research areas 3D printing is applied and which 3D print technologies are currently available. The purposes of the articulated guiding visions provided insight in the aims of the 3D printing applications. Most interviewees clearly declared which purposes they would like to fulfill with their applications, research etc. The concept about required contextual aspects provided good insight in the requirements and environment that stimulate 3D printing. Thereby this concept supported to explore the impact of 3D printing on sustainability/environment, society and safety. However, it must be noted that the interviewees found it challenging to express possible disadvantages of 3D printing and in most cases they were convinced that 3D printing mainly is beneficial. At last, the concept 'normative premises' gave insight in the motives and underlying assumptions that the interviewees have in relation to the development of 3D printing. The interviewees mentioned most of the aspects more implicitly. For example, when tissue engineering researchers mentioned the vision of more patient specific treatments, it became clear that they want better healthcare quality. The first two concepts, current state of knowledge and purposes to be fulfilled, gave insight in the problems that exist and solutions for them. The other two concepts, contextual aspects and normative premises gave insight in the underlying assumptions of the expressed visions.

A caveat regarding the present study which is already described, is about the interviewees who found it difficult to articulated negative impacts of 3D printing. A possible explanation might be that the participants who were included were all business man or researchers, most of the times they focus on the positive sides of 3D printing in order to sell their products or raise money. It would have helped if we included risk experts in the field of 3D printing, because they are more focused on the different impacts that could occur. However, 3D printing only recently received much attention, therefore there were no experts who have much knowledge about the impact of 3D printing. When future research takes place about the impact of 3D printing, ,it is recommended to include risk experts that have knowledge about 3D printing.

5.2 Implications for the RIVM

As described in the introduction and theoretical background the external purpose of this study is to estimate the developments of 3D printing in order to manage this emerging technology in the right direction. The RIVM started a project to investigate which safety and health concerns, as a result of 3D printing, need attention for further investigation and which concerns are current and which are coming. The gathered guiding visions did not raise big concerns or dramatic impacts, yet there are some concerns that are relevant to the RIVM.

5.2.1 Keep an eye on product safety of 3D printed products

During the interviews several concerns are expressed about product safety. As explained in the results there are currently none too little standardizations for the 3D printing process. This has certain impact on the safety of the product users, because due to the lack of standardization it is not guaranteed that the printed product comes out as how it was designed. In context with the vision of '3D printing as a tool to manufacture' this could be considered as a serious concern, because in the future many products will be manufactured by 3D printing.

Another concern that is related to product safety is about the CE mark, which stands for Conformité Européenne. A fabricant indicates with a CE mark that his product satisfies the European requirements in the area of safety, health and environment. Products which do not meet the requirements may not be sold. In the case of 3D printing and especially 3D printers for consumer use, the printed products are not tested to see if they meet the CE standards and regulations. For example, when someone prints a toy for a baby and gives the present away, it is possible that the toy is printed with a plastic which should not come into contact with the mouth or the toy is fragile and breaks into parts which the child could swallow. It is realistic that these scenarios could happen in the future. It is therefore recommended to organize a focus group about this concern and brainstorm with 3D printing actors how to tackle this problem.

5.2.2 *Monitor 'labor' conditions of employees and consumers*

A concern that needs to be taken into account is about the health state of the employees who work with highly density powders. It seems there are no regulations about what protection these employees should wear. Furthermore, the effects of contact with those powders is unknown. The responsibility is currently in hands of the employees. Some employees are careful and prescribe all possible protection wear. However, also some companies seem to take it less carefully. Research about possible health risks and clear guidelines for protection wear might be helpful to protect employees for possible health risks in the future. This of course will also hold for consumers, when SLS type of printers will be introduced to the consumer market. Therefore, it is recommended to conduct a study on the current regulations about the labor conditions and find out if these regulations need to be adapted to guarantee the safe use of 3D printers.

5.2.3 *3D printing is often sustainable, but calculate before you conclude*

Alongside the concerns 3D printing might also bring some positive impact on the environment. Less material is wasted for the production of goods and the production will be mainly on demand, which leads to less stock and less overproduction. Furthermore, less transportation is needed, because products could be printed locally.

Yet the conclusion that 3D printing is a more sustainable manufacturing technique is a bit premature. Firstly, because it is not very likely that 3D printing will take over a large part of the current manufacturing processes. When 3D printing will be limited to a small part of production then the possible associated sustainable impact is not that large. Secondly, as a result of 3D printing the demand for plastic becomes larger, while especially consumers do not always make products with a useful purpose. Thirdly, more research is necessary to claim that 3D printing is a more sustainable manufacturing technique. Simply asking interviewees whether 3D printing is sustainable is perfect for assessing visions, but these are not necessarily science based. To provide a more definite answer to this issue the RIVM should do a Life Cycle Sustainability Assessment. In such an assessment the total environmental impact is calculated, which includes: extraction of the raw materials, manufacturing, transportation, use and disposal.

5.2.4 *Moreover, 3D health care printing is a very positive development*

Another positive development of 3d printing is bio printing. As explained previously, it is likely that living tissue will substitute animal testing for a part. As the RIVM makes extensive use of animal testing, this development must be considered as valuable in order to drop the use of animal testing within the RIVM research centers.

A second reason why the RIVM should foster research in health care 3D printing is the opportunity of health care cost reductions and improvement of the heath care system at the same time. On the long run healthcare might be more personalized, for example the patient could get a personalized treatment like a prostheses due to the use of 3D printing. The chance on complications might reduce which lead to less hospitalizations. It is therefore recommended, to organize a focus group with actors from the healthcare sector and discuss how to flourish healthcare 3D printing in a safe and dignified way.
Continue with CTA to get a grip on risk governance of emerging technologies

Moreover, it is noted that a shortcoming of the CTA until thus far is that the stakeholders included were not very sensitive for possible negative consequences of 3D printing. Consequently, a logical next step in the continuous process of constructive technology assessment will be the inclusion of other stakeholders, who are more inclined to identify negative consequences of 3D printing. This report can serve as the perfect introduction for a dialogue in which e.g risk assessors, 3D printing experts (identified in this study), the Netherlands Food and Consumer Product Safety Authority, assurance companies and Civil Society Organizations can participate. Presenting the guiding visions to them will help them to oversee the future directions and helps them to formulate possible risks or concerns. For a successful dialogue it is needed to limit the scope and to choose a more specific subject such as health care printing or food printing.

6 Conclusion

The aim of this study was to gain more insight in the future development of 3D printing and the impact of it on sustainability/environment, society and safety . In this chapter an answer is provided to the main research question of this study, which was:

> *What are the guiding visions concerning 3D printing applications and their impact on sustainability, safety and society, held by the 3D printing developers and users?*

Overall, it can be concluded that this research project provided insight into guiding visions held by scientists and technology developers in four different domains. These four domains are industrial, consumer, healthcare and food 3D printing. In the paragraphs below we provide the visions identified in the terms of the theoretical framework as outlined in chapter 2.

6.1 Vision on industrial 3D printing

6.1.1 Purposes to be fulfilled

The research question regarding the purposes to be fulfilled covers the expectations and objectives of the actors about the future use of the technology and what technology developments are relevant in the perspective of the actors. These purposes are presented in Table 6.1. They envisioned that 3D printing becomes a common manufacturing technology that will produce products that are small in volume and customized. Furthermore, 3D printing will still be used to build prototypes. At last, they expected that the 3D printing manufacturing process will be on demand and therefore more flexible then other manufacturing processes.

3D printing as tool to make prototypes
3D printing as tool to manufacture end parts without assemblage
Flexible and on demand production
Multi material 3D printers
Customized products

Table 6.1: Purposes of industrial 3D printing

6.1.2 Current state of knowledge and technology

This study has shown that 3D printing has to make many improvements before it becomes a mature technology. Most research in this domain aims to improve the printing technology. It is desired to build printers that on one hand have a better resolution and on the other hand print at high speed. At this moment, the most common 3D printing technologies used in this domain are FDM, Material Jetting, SLA and Powder bed fusion/ SLS. Moreover, an expansion of the variety of material types is desired. Thereby, more knowledge is required about the change of material properties, after the printing process. It is unknown if the properties of material chance and therefore the quality of the products could not always be guaranteed. Furthermore, the next few years, multimaterial printers will be developed. To make industrial 3D printing a mature manufacturing technology, research is needed to improve the technology, hardware, software and print materials in order to develop better 3D printers that are more reliable, precise and quicker.

6.1.3 *Relevant contextual aspects*

To reach the desirable applications of 3D printing, various conditions and circumstances are needed. Two aspects that contributed to the success of 3D printing is the digitalization of designs and the open source access to these designs. These aspects also contribute to the further growth of 3D printing in the industrial domain. When designs will increasingly be digitalized and available, it could be expected that the use of 3D printing to manufacture the designs will increase. Sharing information and knowledge is therefore an important condition for further growth and development of 3D printing. Furthermore, a successful business case of the desired applications is another important aspect. The costs and benefits will be weighed and eventually give decisive whether there will be continued with the development of an application. Another condition which is desired is a safe and standardized 3D printing process. In addition, not all materials are suited for every application. Therefore, consideration must be given to the materials with certain properties, which match with the product properties that is printed.

6.1.4 *Normative premises*

The 3D print developers and users from the industry domain did not explicitly articulate norms, values and motives of the desired final state. Although implicitly, they mentioned that the dominant motive for the development of 3D printing in the industry was increasing the quality of the products and cost reductions in the manufacturing process. Nevertheless, the sustainability of 3D printing might also be a driving factor behind the technique. In general, 3D printing is seen a sustainable technology which has a good impact on the environment. Less material is wasted and due to the possibility of on demand production, fewer inventories are necessary. In addition, the impact of 3D printing on the logistic cycle might lead to less transportation and therefore have a smaller carbon footprint. Some experts even had the motive to create a circular economy and 3D printing suits this goal well.

6.2 Vision on consumer 3D printing

6.2.1 *Purposes to be fulfilled*

The developers of consumer 3D printers expressed different ambitions and visions about the desired future use of consumer 3D printing, which are presented in table 6.2. Firstly, they have the ambition to make 3D printing as manufacturing technology more accessible for consumers. In this way they envisioned that society will have more room for creativity and are able to design their own products or adapt existing designs. Secondly, they have the desire to evolve this technology into a common used technology that will end up in every household. Consumers will use it for example to print different end products, prototypes of own designs and production of spare parts. As described in the discussion it is questionable if this last desired purpose is feasible.

3D printing as tool that makes manufacturing more accessible
3D printing as tool to manufacture local or at home

Table 6.2: Purposes of consumer 3D printing

6.2.2 *Current state of knowledge and technology*

Even more as in the industrial domain consumer 3D printing is in its infancy. Currently, the consumer printers offer too few opportunities and do not consequently deliver good quality prints. The most common 3D printing technologies used in this domain is FDM, but other techniques like Material Jetting, SLA and Powder bed fusion/ SLS will be used in the future. Like it is in the industrial domain a significant improvement on the resolution-speed ratio is needed and more research on appropriate materials and the development of multimaterial printers is needed to fulfill the desired purposes.

6.2.3 *Relevant contextual aspects*

For consumer 3D printing, more or less the same contextual aspects apply as for industrial 3D printing, access to and sharing of designs is desired. Currently, a driving force of consumer 3D printing is the open source databases of designs. Online communities are formed to share knowledge and 3D print designs. In the future it is desired that these communities will expand and many more people will share their knowledge and designs on the internet. Moreover, the business case of consumer 3D printing is an important aspect that will have influence on the future use of consumer 3D printing. With the desired developments of good quality multimaterial consumer printers in mind, it is questionable if consumer 3D printing remains affordable for the average household. This may hamper developments severely as the sanity of this case is doubted by experts. Another circumstance, which plays a role in consumer 3D printing, is acceptation. For consumer printing both the enthusiasm and acceptance of the technology by society is of great importance for the achievement of the desired applications. In addition, prerequisite for societal acceptation is that printers have to be safe and easy to use. It must be determined if certain techniques are safe enough for non-professional use. The government also should be aware of the consequences, like the loss of control on product safety, when people print at home. They have to find a solution for it to get a safe course of 3D printing. At last, the digital designs that are for sale must be protected to prevent that people get those designs for free from the internet.

6.2.4 *Normative premises*

From this study it appeared that the underlying norms and values for consumer printing are to give society more freedom of choice. The society might no longer be dependent on the industry, because fabrication of own designs becomes accessible and products become more adapted to the individual, because consumers will be able to adapt designs to their wishes. Furthermore, like it is for industrial 3D printing, consumer 3D printing may have a positive impact on the environment. It is perceived as valuable that consumers could recycle their own products to make new products with it. In this way the economy becomes more circular.

6.3 Vision on food printing

6.3.1 *Purposes to be fulfilled*

The developers of food printers expressed different ambitions and visions about the desired future use of food printing. It is desired to have food printers in the near future that will be used in the food industry (Table 6.3). These printers could print for example many different customized chocolates in once. It is also desired to make consumer food printers which have more opportunities then the industrial food printers. These consumer food printers will print different types of food, like bread, meat, pasta, chocolate etc. Consumers will use these printers to make their daily meals. Furthermore, it is desired by the food print developers to print personalized food. Every meal will contain the perfect amount of ingredients for that one specific person. At last, it is desired to make new food, which yet cannot be imagined.

(Consumer) foodprinters
Personalized food
New food

Table 6.3: Purposes of 3D food printing

6.3.2 Current state of knowledge and technology

Currently, food printing is in a experimental phase, therefore the applications are limited. At this moment, it is only possible to print with materials like pureed food and chocolate. This implies that there is a large hurdle to take food printing to the desired level, because food printing is mostly multimaterial. In addition, the desired consumer food printers should print different types of food and may therefore be more complex and need more time to develop than food printers for industrial use. Therefore, it could be concluded that it will take long to fulfill the desired purposes.

6.3.3 Relevant contextual aspects

The relevant contextual aspects show many similarities with the aspects of consumer printing. Firstly, the business case of food printing is uncertain. Because of the small number of applications and the great uncertainty surrounding the potential of food printing it is hard to say if food printing will have an interesting business case. Secondly, an aspect, which is likely to play a large role in the development of food printing is acceptation. For food printing also both the enthusiasm and acceptance of the technology by society is of great importance for the achievement of the desired applications. It might be possible that the society perceive food printing as unnatural, which will hamper the development of the desired purposes. At last, the food printing process and the printed food must be safe

6.3.4 Normative premises

Among the food printing developers the motive of the developments was to increase the food quality and to make the society more healthier. They all want to improve the food by make it personalized and in that way they desired to contribute to a healthier society. Furthermore they want to contribute to a more sustainable food chain. Firstly, because the food used in food printers may be obtained from food that would be thrown away otherwise. This waste flow could decrease. Secondly, food printing may help lowering the carbon footprint by using substitute proteins. If it will be possible to print meat substitutes that have the interest of the whole society, less meat will be produced. Cattle breeding has high emissions of carbon, therefore when less cattle breeding is needed it may decrease de carbon percentage in the air.

6.4 Vision on healthcare printing

6.4.1 Purposes to be fulfilled

Bioprinting researchers and other healthcare application experts mainly focused on increasing the quality of life and healthcare. This could be achieved by patient specific healthcare due to customized devices and other applications and the use of tissues for research and transplantation. The desired future purposes are presented in Table 6.4. It is desired that in the future all surgeons have access to and use patient specific 3D printed models on which they could practice their surgery. During the surgery they could use customized medical instruments like saw models. Furthermore, more access to customized (hybrid) prosthesis is desired. Moreover, the bioprinting researchers have great expectations about the use of printed tissue in the future. They envisioned that animal testing will be substituted for a part, which will reduce the use of animals for research. Furthermore, it is desired that the printed tissue will be used for drugs and toxicity screening studies. At last, it is desired to use living tissue as regenerative medicine, to replace non-functional tissue in the human body.

Surgery planning
Custom medical instruments
Customized (hybrid) prostheses
Tissue engineering
Partly substitute animal testing
Drugs screening
Toxicity screening
Regenerative medicine

Table 6.4: Purposes of 3D healthcare printing

6.4.2 *Current state of knowledge and technology*

Currently, there is a big difference in maturity between surgery planning, ccustom medical instruments, customized (hybrid) prostheses at the one hand and tissue engineering at the other hand. The first three applications are already applicable, but not widely. To make these applications a more common development it is needed to increase the quality of the printed instruments or models. Tissue engineering is in an experimental phase, many developments are needed to achieve the desired purposes. Like it is in other domains a significant improvement to the bio printers is needed to make them more accurate and fast. In addition, more research on appropriate bio inks is needed to fulfill the desired purposes. Although, most of the research that will lead to the application of tissue engineering does not involve bio printing related research, but cell related research questions, like how do cells adhere to each other after they are printed.

6.4.3 *Relevant contextual aspects*

As in the other domains acceptation and sharing of knowledge are important factors that will influence the development of healthcare printing. Acceptation refers firstly to the use of applications by healthcare workers like surgeons. If they are resistant towards the use of these tools then the desired purposed might not be fulfilled. Secondly, development of printing cells, tissues and possibly even organs is dependent upon societal acceptance. Also in this domain it is relevant that the printed objects, like prostheses, are safe and strong enough to implant them.

6.4.4 *Normative premises*

The experts in healthcare 3D printing strived for an improvement of the quality of care and improvement of quality of life of people. They envisioned a society in which more healthcare options and prevention strategies become available. This will lead to a society where more patient based health care is provided and the quality of healthcare is improved. Furthermore, it is perceived as valuable that 3D print technologies contribute to a reduction of healthcare costs.

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8 Appendix 1: Overview of 3D print actors in the Netherlands

#	Organisation/ company	Expertise
1	Ultimaker	Developer of consumer 3D printer
2	Leapfrog	Developer of consumer 3D printer
3	Océ	Developer of Industrial 3D printer
4	Additive Industries	Developer of Industrial metal 3D printer
5	TU Delft	Research on 3D printing
6	TU Eindhoven	Research on 3D printing materials and bio-engineering
7	Universiteit Utrecht	Research on bio printing and medical printing
8	Vrije Universiteit Amsterdam	Research on bio printing and medical printing
9	Better future factory	Developer of recycled 3D printing material
10	Fablabs (De Waag, Protospace)	Provider of manufacturing techniques
11	TNO	Research on Additive manufacturing and food printing
12	Top bv.	Research on food printing
13	Nationaal Lucht- en ruimtevaartlaboratorium	Research on industrial printing
14	Shapeways	3D printing service provider
15	ColorFabb	Developer of (sustainable) filament
16	Het Foodatelier	Research on food printing
17	Radboud Universiteit	Research on bio printing and medical printing
18	Mauk Cc	Developer of consumer 3D printer
19	Kemo modelmakerij bv	3D printing service provider
20	3D systems (BeNeLux)	3D printing service provider and developer of 3D printers
21	Ground3D	3D print platform
22	DSM	Research on 3D print material

9 Appendix 2: Text of the invitational letter

Geachte (nader invullen),

Het RIVM is recent gestart met een onderzoek dat de ontwikkeling van 3D printen in kaart wil brengen. Doel hiervan is enerzijds dat we positieve ontwikkelingen niet in de weg staan en anderzijds dat we eventuele negatieve effecten vroegtijdig in het vizier krijgen. Om een zo goed mogelijk beeld te creëren van de toekomstige ontwikkelingen, willen wij graag met mensen in gesprek die aan het begin van de ontwikkelingen staan. Wij zijn daarom zeer geïnteresseerd in uw verwachtingen ten aanzien van de ontwikkeling van 3D-printen.

Graag willen wij u uitnodigen voor een interview, waarin wij op zoek gaan naar uw visie op de toekomst van 3D-printen. Het interview zal bij voorkeur plaatsvinden in de weken 17-21 en zal ongeveer een uur duren. Wij komen hiervoor naar een voor u handige locatie.

Eind mei (datum wordt nog nader bepaald) organiseren wij een focusgroep/workshop met meerdere 3D-print deskundigen (verschillende toepassingsdomeinen). De focusgroep biedt voor u een mooie gelegenheid om met andere deskundigen in gesprek te gaan en uw eigen verwachtingen te toetsen. Ook hiervoor willen wij u van harte uitnodigen.

Binnenkort nemen wij telefonisch contact met u op met de vraag of u mee wilt werken aan ons onderzoek, hetzij alleen door middel van een interview of interview en focusgroep. Uiteraard kunt u ook zelf contact met ons opnemen.

Mocht u nog vragen hebben, schroom dan niet die te stellen. Anders hopen we u voldoende te hebben geïnformeerd, en kijken we uit naar een interview met u.

Met vriendelijke groet,

Jeroen Devilee (jeroen.devilee@rivm.nl)
Maaike den Heijer (maaike.den.heijer@rivm.nl)

Centrum voor Duurzaamheid, Milieu en Gezondheid

10 Appendix 3: Participants in the qualitative study

#	Expertise	User/developer
1	Expert in 3D printing engineering	User
2	Expert in desgin methods for 3D printing	User
3	Developer of industrial printer	Developer
4	Expert in 3D print materials	user/developer
5	Expert in 3D printing & circular economy	User
6	Expert in 3D printing & circular economy	User
7	Expert in 3D printing & marketing	User
8	Developer of industrial 3D printer	Developer
9	Expert in 3D printing technologies	Developer
10	Expert in industrial and consumer 3D printing	User
11	Expert in 3D printing & aerospace	user/developer
12	Developer of consumer 3D printers	Developer
13	Director of a fablab	User
14	Developer of consumer 3D printers	Developer
15	Expert in food printing	Developer
16	Expert in food printing	Developer
17	Expert in healthcare applications of 3D printing	User
18	Expert in healthcare applications of 3D printing	User
19	Expert in healthcare applications of 3D printing	User

11 Appendix 4: Interview guidance

A Introductie

Goedendag, mijn naam is Maaike den Heijer en dit is .. (afhankelijk van wie er mee is). Dank u wel dat u mee wilt werken aan ons onderzoek, dat waarderen wij zeer. Misschien is het een goed idee dat wij eerst nog even wat over ons project vertellen, voordat we verder gaan. Het RIVM is de ontwikkeling van 3D printen en zijn vele toepassingen niet ontgaan en wil daarom een verkennend onderzoek doen die de toepassingen en mogelijke impact daarvan in kaart wil brengen. Dit vanuit een perspectief dat wanneer je er zo vroeg mogelijk mee begint we de positieve ontwikkelingen mogelijk kunnen gaan stimuleren en eventuele negatieve ontwikkelingen kunnen voorkomen of remmen. Het doel van het onderzoek is om de visies van verschillende 3D print actoren te verzamelen om op die manier inzicht te krijgen van de ontwikkeling van 3D printen. In dit interview willen we dus uw visie over de ontwikkeling van 3D-printen 'achterhalen' en met u daarover in gesprek gaan. Voordat we verder gaan wil ik u vragen of u het goed vind als we dit gesprek opnemen, de gegevens zullen geheel anoniem behandeld worden. Vindt u dit goed? Verder wil ik u er nog op wijzen dat u altijd vrij bent om niet te antwoorden of het interview te stoppen. Hebt u nog vragen of onduidelijkheden die uitgelegd moeten worden voordat we verder gaan?

B Algemeen

1. Kunt u mij misschien iets meer vertellen over uw toepassing/onderzoek/product?

2. Wat wilt u bereiken met uw toepassing/onderzoek/product, wat is uw ambitie?

3. Hoe denkt u dat uw toepassing/onderzoek/product zich zal ontwikkelen in de toekomst?

4. Wat zijn de reacties vanuit de samenleving op uw toepassing/onderzoek/product?
   Wanneer niet bekend: wat denkt u dat de reactie is?
   Wanneer negatief: wat vind u daarvan?

C Toekomst

Ik wil u vragen om het jaar 2060 in te beelden waarin 3D printen volledig is ingebed en al uw wenselijke toepassingen gebruikt worden. Vanuit dit perspectief:

1. Kunt u mij beschrijven hoe u wenst dat deze toekomst eruit zal zien, m.b.t. op 3D printen?

2. Welke wenselijke toepassingen zullen er volgens u zijn in 2060?

- Zou er mogelijk ook bezwaar kunnen zijn op deze toepassingen?

3. In welke domeinen zal 3D printen gebruikt worden, bijvoorbeeld gezondheidszorg?

4. In welk domein verwacht u veel ontwikkeling?

5. Welke ontwikkelingen zijn nog nodig om tot zo'n wenselijke toekomst te komen?

6. Wat lijkt u niet wenselijk aan de ontwikkeling van 3D printen?
   - Kunt u misschien voorbeelden noemen, van bijvoorbeeld niet wenselijke toepassingen?

D Impact

In dit onderzoek zijn we ook geïnteresseerd in de effecten/impact die 3D printen heeft op drie aspecten: duurzaamheid en milieu, veiligheid en samenleving.

1. Wat voor een effect/impact voorziet u op duurzaamheid/ milieu?
2. Heeft u misschien voorbeelden van toepassingen die positief dan wel een negatief effect hebben?

3. Hoe veilig is het gebruik van 3D printen, oftewel hoe veilig zijn de materialen en hoe veilig is het gebruiken van en 3D printer?
   - Voorziet u mogelijke risico's die op het gebied van veiligheid in de toekomst?

4. Wat voor een effect/impact voorziet u op de samenleving?
5. Heeft u misschien voorbeelden van toepassingen die mogelijk een positief dan wel negatief effect hebben?

E Afsluiting

Volgens mij hebben we nu alle relevante dingen wel besproken. Hebt u verder nog vragen of opmerkingen?

Dan heb ik nog twee vragen voor u:

1. Heeft u misschien nog literatuur suggesties die voor ons onderzoek relevant zijn?

2. Weet u mogelijk nog andere mensen die interessant zijn om te interviewen?

Wederom hartelijk dank voor uw medewerking. Ik zal u binnen twee weken een samenvatting van dit gesprek opsturen, dan kunt u dat controleren en met eventuele opmerkingen terug sturen.

12 Appendix 5: Atlas.ti Coding sheets

Industrie	
Code	*Categorie*
volledige ontwerp vrijheid	now-2060
automobiel en luchtvaart	now-2060
kleine series	now-2060
Ideeen omzetten naar fysiek	now-2060
open source -> oplossen problemen	now-2060
rapid prototyping	now-2060
3D printen niet de oplossing voor alles	now-2060
ontwerp bedenken is genoeg	now-2060
voordeel: complexe vormen maken	now-2060
niet helemaal 0% waste	now-2060
Nederland loopt achter	Now
ontwikkelingen: Industrie > consumenten markt	Now
gebruik 3Dp niet gevaarlijker dan andere	Now
industrie afwachtend	Now
materialen/software markt dominantie	Now
niet alle materiaal recyclebaar	Now
intelectueel eigendom issue valt wel mee	Now
industrie enthousist over metaal printer	Now
intelectueel eigendom van alle tijden	Now
recyclen kan vergeten worden	Now
nieuw materiaal op markt krijgen duurt lang	Now
geef industrie de ruimte	Now
materiaal producent is beperkt -> slim zijn	Now
wetgeving remt innovatie	now
weining onderzoek naar nieuw materiaal	now
metaal poeder recyclebaar	now
Current materials	now
combinatie van klassiek en 3D tech	jaar 2060
shift naar ondemand/ flexible	jaar 2060
functionele producten zonder assamblage	jaar 2060
meer customization	jaar 2060
volledige recycling en reproductie	jaar 2060
shift prototyping endparts	jaar 2060
wordt een gewone techniek	jaar 2060

hoop op on demand en recycling	jaar 2060
massa < ondemand productie	jaar 2060
circulaire economie	jaar 2060
meer complexiteit	jaar 2060
wat kan dat gaat gebeuren	jaar 2060
minder transport	jaar 2060
betere producten	jaar 2060
decentrale massa productie	jaar 2060
nieuw product	jaar 2060
van waardeloos naar waardevol	jaar 2060
betaalt voor prestatie	jaar 2060
over 30 jaar al oud	jaar 2060
plastic soup & recyclen	jaar 2060
veel toepassing in maak industrie	jaar 2060
robotica en 3Dp	jaar 2060
customization naar decentrale productie	jaar 2060
shift lokale productie	effect
minder restafval	effect
verlies banen en nieuwe banen	effect
minder voorraden/opslag	effect
consument heeft meer inspraak	effect
distributie: grondstoffen > producten	effect
logistieke verandering	effect
grondstof prijzen veranderen	effect
markt gaat wakker geschud worden	effect
meer open samenleving	effect
kosten grondstoffen > producten	effect
vliegtuigen iets milieuvriendelijker	effect
niet alle materialen printen	effect
complexe vormen niet duurder	effect
3Dp & 3D scannen	development-2060
eigenschappen niet bekend	development
roep naar standaardisatie	development
nauwkeurig vs snel	development
multi materialprinten	development
uitbreiden materialen pallet	development
gezondheids effect materialen (poeders) onbekend	development
nieuwe marketing	development
mergen technieken is uitdaging	development
ontwikkeling in software	development

van hoogwaardig naar hoog & laag waardig	development
recycling uitvinden: makers > industrie	development
multi material niet recyclebaar	development
Sexindustrie	development
ontwikkeling metaal printer	development
fullcollar printen	development
recycle machine in ontwikkeling	development
rijksoctrooi aanpassen	development
plastic recycling in buitenland	development
recycled plastic wordt goedkoper	developement
gebruik in onderwijs belangrijk	condition
invloed internet / digitalisering	condition
kosten gedreven	condition

Consumer printing	
Code	*Categorie*
ontwerp bedenk is genoeg	now-2060
online database	now-2060
ideen omzetten naar fysiek	now-2060
weinig onderzoek naa nieuw materiaal	now
makers beweging geen kopiergedrag	now
nu vooral makers	now
toename fablabs	now
fab labs moeite met financiering	now
verbruik plastic nu groter: verspilling	now
opensource -> oplossen problemen	now
ontwikkelingen: industrie > consumenten	now
minder fysieke winkels	effect
kosten grondstoffen > producten	effect
stap voor ondernemer naar de markt minder groot	effect
gepersonaliseerd -> minder weggooien	effect
gevaar: materiaal keuze -> toepassing	effect
geengevaar -> materiaal keuze	effect
ruimte voor creativiteit	effect
consument heeft meer inspraak	effect
meer toegankelijkheid voor de consument	effect
eerst scholen dan samenleving	development-2060
fullcolar printing	development
shaft van makers naar consument	development
mergen technieken is uitdaging	development
ontwikkeling in software	development

uitbreiden materialen pallet	development
multi material	development
nauwkeruig vs. Snel	development
niet alle materialen printen	condition
opensource stimullert delen	condition
metaal printers thuis -> businesscase	condition
recyclen kan vergeten worden	condition
veiligheid hangt af van gebruiker	condition
gebruik 3D printen in geventileerde omgeving	condition
dummyproof printer voor weinig	condition
thuis geen poeders printen	condition
bescherming van ontwerpen	condition
geen overstap naar huis	2060
consument heeft vrijheid om te recyclen	2060
meer open samenleving	2060
consumer wordt prosumer	2060
volledige recycling en reproductie	2060
service/copy shops	2060
geen assamblage	2060

Healthcare printing	
Code	*Categorie*
voordeel: customizen medische toepassingen	now-2060
maakt onderzoek makkelijker	now-2060
grootse impact bij regenerative medicin	now-2060
business case medisch is anders	now-2060
in gezondheidszorg gaat het langzamer	now-2060
ziekenhuis staf terughoudend	Now
bio printen: gaat om materiaal & ontwerp	Now
huidige bioprinters nog niet goed	Now
media schept te hoge verwachting van bioprinten	Now
zorgverzekering vergoed nog niet	Now
meer subsidie voor bioprinten	Now
verbetering kwaliteit van leven	Effect
kostenbesparing zorg	Effect
scaffolds printen	development-2060
operatieplanning & prothese eerste stap	Development
bio-printmateriaal is uitdaging	Development
software ontwikkeling voor implantaten	Development
bioprinten = scaffolds printen	Development
kraakbeen ontwikkeling	Development

hoeveel organisatie aanbrengen?	Development
ontwikkeling bio-printer	Development
biomateriaal in ontwikkeling	Developement
willen we geprinte organen?	condition
goede verdeling van technologie en kennis	condition
bioprinten moet academisch	condition
gebruik bioprinten -> nieuwe generatie	condition
bioprinten & screening/testen	2060
bioprinten & regenarative medicine	2060
orgaan printen heel ver weg	2060
hybride constructen maken	2060
nieuw product	2060
bio printen niet voor iedereen	2060
medische voordelen voor iedereen beschikbaar?	2060
operatieplanning wel voor iedereen	2060
bioprinten & regenarative medicine al in 2060	2060
weefsel printen vs. dierproeven	2060
prothese worden toegankelijker	2060

Food printing	
Code	*Categorie*
voedselveiligheid non-issue	now-2060
matige acceptatie food printing	now-2060
food printing overschat	now
complexiteit van voedsel is hoog	now
allen processed foods	now
voedsel print beperkt	now
restaurant enthousiast	now
minder gekookt	effect
hightech vs. Romantici	effect
geen smaakvervlakking	effect
gevarieerd voedsel toegankelijk	effect
kostenbesparing zorg	effect
benadering van voedsel	development-2060
voedsel textuur printen	development
voedsel printen voor ouderen mensen	development
veelzijdig voedsel: industrie < consument	development
3D print proces aanpassen aan voedsel printen	development
voedsel: industrie -> consument	development
goedgekeurde ingredient	condition
voedsel: moet je alles printen?	condition
nieuwe inhoud/ nieuwe structuren van 'vieze' producten	2060

voedsel afvalstromen gebruiken	2060
voedsel cardridges	2060
voedselprinten & stadslandbouw	2060
gepersonaliseerd voedsel	2060
voedsel printen thuis	2060