



Siddharth Jayaprakash

## **Role of Prosumer Driven 3D Food Printing in Innovating Food Value Chains**

Thesis submitted in verification of the professional development required for the degree of Master of Science (Technology).

Espoo, 27.11.2017  
Supervisor: Professor Jouni Partanen  
Advisor: Dr. Iñigo Flores Ituarte

---

**Author:** Siddharth Jayaprakash

---

**Title of Thesis:** Role of Prosumer Driven 3D Food Printing in Innovating Food Value Chains

---

**Degree:** Master of Science in Technology

---

**Major/Minor:** Mechanical Engineering/International Design  
Business Management (IDBM)**Code:** ENG25

---

**Thesis Supervisor:** Professor Jouni Partanen

---

**Thesis Advisor:** Dr. Iñigo Flores Ituarte

---

**Date:** 27.11.2017**Number of Pages:** 88 + 18**Language:** English

---

Digital platforms have created an impact in almost all facets of our life in a short period. Today, they are an integral and critical part of consumer experience. When combined with revolutionary 3d printing technology, these platforms are great enablers of prosumption, i.e., production undertaken by consumers. The associated paradigm change is already visible in the specialized goods sector. With the emergence of 3d food printing technology, similar changes are very much anticipated in the food sector.

The purpose of this master's thesis is to create an understanding on how digitally-driven 3d food printing could be best utilized for food prosumption. Three research questions were raised with an aim of identifying key challenges, and uncertainties in prosumer driven 3d food printing; defining the characteristics and customization parameters of a prosumer platform for 3d food printing; and identifying most potential archetypes and use cases for prosumer-driven 3d food printing. To answer the research questions, 3 research themes were identified, namely food value chain, prosumption, and 3d food printing.

After an extensive literature review process based upon the research themes, relevant data were gathered using Mixed Methods Research (MMR) approach. 15 semi-structured interviews were conducted with experts from industry and academia. This was followed by a quantitative survey with a pool of respondents from within the identified research themes. Finally, a stakeholder workshop was carried out to finalize and further refine the concepts generated through MMR.

Personalized nutrition is found to be an area where 3d food printing has a lot of scope, especially for applications in fitness centres, senior homes, and hospitals. Also, utilization of prosumer driven 3d food printing in fine dining restaurants has one of the highest business potential and feasibility at this point of time. Overall, the research implies that leveraging digital platforms in 3d food printing has the potential to generate futuristic food value chains that are connected, collaborative, data-driven, and transparent.

---

**Keywords:** 3D Food Printing, Digital Platforms, Prosumption, Food Production, Food Consumption, Food Value Chains, Mixed Methods Research, Qualitative Research, Quantitative Research, Use-Cases

---

## Preface

I am filled with gratitude towards Professor Jouni Partanen and Dr. Iñigo Flores Ituarte for giving me the amazing opportunity to work on this research topic. The guidance and support given by Iñigo was invaluable for the successful completion of this master's thesis. I also want to thank all members of the Additive Manufacturing research group at Aalto University for the encouragement and support given. This master's thesis is part of a jointly-funded Tekes (Finnish Funding Agency for Innovation) project – 3D Surprise (Multi-layer food textures by advanced manufacturing technologies), in collaboration with VTT Technical Research Centre of Finland, Aalto University, and Finnish industry partners. I would like to acknowledge the guidance and support given by the stakeholders of 3D Surprise project during the data collection phase. I would also like to express my sincere gratitude towards all the participants of interviews, survey, and workshop that were conducted as part of the thesis research. Last but not the least, I want to thank my family and friends for encouraging and supporting me throughout!

Espoo 27.11.2017

*Siddharth Jayaprakash*

Siddharth Jayaprakash

# Table of contents

Abstract	
Preface	
Table of contents.....	7
List of figures and tables.....	9
Figures.....	9
Tables.....	10
Abbreviations.....	11
1 Introduction.....	12
1.1 Background.....	12
1.2 Research gap.....	13
1.3 Scope and intended contribution.....	14
1.4 Thesis timeline.....	16
1.5 Thesis organization.....	16
2 Theory and state of the art.....	17
2.1 The food value chain.....	17
2.2 Future of food.....	20
2.2.1 Future of food production.....	21
2.2.2 Future of food distribution and consumption.....	22
2.3 The era of prosumers.....	23
2.3.1 Evolution of prosumption.....	25
2.3.2 Prosumer driven 3d printing: A new manufacturing paradigm.....	26
2.3.3 Enablers of future prosumption.....	27
2.4 3d printing of food.....	28
2.4.1 Ingredient portfolio for 3d food printing.....	29
2.4.2 3d food printing technologies.....	30
2.4.3 Significance of 3d food printing.....	36
2.4.4 Market segmentation.....	37
2.5 Current 3d food printing ecosystem.....	38
2.5.1 Existing 3d food printing value chains.....	39
2.5.2 Existing 3d food printers and research prototypes.....	41
3 Research design.....	45
3.1 The process: Double diamond process model.....	45
3.2 Data collection paradigm: Mixed methods research.....	47
3.2.1 Mixing the data.....	49
3.2.2 Qualitative research: Semi-structured interviews with experts.....	50
3.2.3 Quantitative research: Online survey for experts.....	53
3.2.4 Challenges in mixed methods research.....	57
3.2.5 Stakeholder workshop.....	57
4 Research findings.....	59
4.1 Findings from qualitative research.....	59
4.1.1 Change drivers.....	59
4.1.2 Challenges/constraints.....	60
4.1.3 Uncertainties.....	61
4.1.4 Characteristics of a prosumer platform for 3d food printing.....	62
4.1.5 Customization parameters for prosumer driven 3d food printing.....	63
4.1.6 Potential use-cases for prosumer driven 3d food printing.....	63

4.2	Findings from quantitative research.....	65
4.3	Further developments.....	72
4.3.1	3d food printing vending machines.....	72
4.3.2	3d food printing in fine dining.....	73
4.3.3	3d food printing for fitness enthusiasts.....	74
5	Discussion.....	76
5.1	Results and implications.....	76
5.2	Challenges.....	77
5.3	Future directions.....	78
6	Conclusions.....	79
	References.....	80
	Appendix.....	88
	Appendix 1. Interview framework.....	i
	Appendix 2. Survey framework.....	iii
	Appendix 3. Workshop framework.....	x
	Appendix 4. Posters for 3 use-cases.....	xiii
	Appendix 5. Selected quotes from interviews.....	xvi

# List of figures and tables

## Figures

Figure 1: Innovations that changed the way we consume food.....	13
Figure 2: Research themes.....	15
Figure 3: Master's thesis timeline.....	16
Figure 4: A simple food value chain.....	18
Figure 5: An extended food value chain.....	19
Figure 6: Future meatballs made from alternate ingredients (Poel, 2016).....	22
Figure 7: Three waves in human history according to Alvin Toffler.....	24
Figure 8: Four steps of AFM (Zoran and Coelho, 2011; Sun, Peng, Yan, et al., 2015).....	29
Figure 9: Soft material-extrusion 3d printing (Source: Natural Machines).....	31
Figure 10: Chocolate structure made using melting extrusion (Source: ChocEdge).....	32
Figure 11: Food objects created by TNO using SLS (Source: TNO).....	33
Figure 12: Sugar structure made using SHASAM (Source: Evil Mad Scientist).....	33
Figure 13: Chocolate structure made using LB technology (Source: 3D Systems).....	34
Figure 14: Market segmentation for 3d food printing.....	38
Figure 15: 3d food printing ecosystem highlighting main actors.....	39
Figure 16: A food value chain with 3d food printing: Consumer buys 3d printed food.....	40
Figure 17: A food value chain with 3d food printing: Consumer buys 3d food printer.....	40
Figure 18: Food structures made of insect powder (Soares, 2011).....	41
Figure 19: Research process: The double-diamond process model.....	46
Figure 20: Key characteristics of MMR (Greene, Caracelli and Graham, 1989).....	47
Figure 21: Four ways of mixing data in MMR (Curry et al., 2013).....	49
Figure 22: Overview of semi-structured interviews conducted.....	52
Figure 23: Affinity diagrams being made with the help of post-its.....	53
Figure 24: Location of survey respondents.....	55
Figure 25: Primary field of organization of survey respondents.....	56
Figure 26: Field of expertise of survey respondents.....	56
Figure 27: Stakeholder workshop steps.....	57
Figure 28: Stakeholder workshop conducted as part of the thesis.....	58
Figure 29: Change drivers for prosumer driven 3d food printing.....	60
Figure 30: Challenges/constraints of prosumer driven 3d food printing.....	61
Figure 31: Uncertainties regarding prosumer driven 3d food printing.....	62
Figure 32: Mainstreaming of 3d food printing.....	65
Figure 33: Evaluation of hypotheses from interviews.....	66
Figure 34: Key characteristics of a prosumer driven platform for 3d food printing.....	67
Figure 35: Desirability of customization parameters.....	68
Figure 36: Feasibility of customization parameters.....	69
Figure 37: Businesses potential of use-cases.....	70
Figure 38: Feasibility of use-cases.....	71
Figure 39: Prosumer work-flow for 3d food vending.....	73
Figure 40: Prosumer work-flow for 3d food printing in fine dining.....	74
Figure 41: Prosumer work-flow for personalized nutrition in fitness centres.....	75

## Tables

Table 1: Research questions. ....	14
Table 2: Three types of prosumption (Rayna, Striukova and Darlington, 2015). ....	25
Table 3: 3d food printing technologies (Godoi, Prakash and Bhandari, 2016). ....	35
Table 4: 3d food printer designs and research projects. ....	43
Table 5: Restaurants/ food producers utilizing 3d food printing. ....	44
Table 6: Comparison of qualitative and quantitative methods (USDE, 2014). ....	48
Table 7: Details about the semi-structured interviews.....	52

## Abbreviations

3d	Three-dimensional
3DP	Three-dimensional Printing
AI	Artificial Intelligence
AFM	Additive Food Manufacturing
AM	Additive Manufacturing
AMF	Additive Manufacturing file format
B2B2C	Business to Business to Consumer
B2B	Business to Business
B2C	Business to Consumer
CAD	Computer Aided Design
CAGR	Compound Annual Growth Rate
CD	Customer Dominant
DIY	Do it Yourself
EU	European Union
FAO	Food and Agriculture Organization
FLM	Food Layered Manufacturing
GD	Goods Dominant
GUI	Graphical User Interface
ICT	Information and Communication Technology
IFTF	Institute for the Future
IoT	Internet of Things
IT	Information Technology
LB	Liquid Binding
MIT	Massachusetts Institute of Technology
MMR	Mixed Methods Research
NASA	National Aeronautics and Space Administration
NGOs	Non-Governmental Organizations
R&D	Research and Development
RepRap	Replicating Rapid Prototyper
RIG	Robots In Gastronomy
SD	Service Dominant
SHASAM	Selective Hot Air Sintering and Melting
SLS	Selective Laser Sintering
SMEs	Small and Medium-sized Enterprises
STL	STereoLithography file format
TNO	Netherlands Organisation for Applied Scientific Research
UK	United Kingdom
UN	United Nations
USA	United States of America
USD	United States Dollar
USDE	United States Department of Energy
VR	Virtual Reality
VSP	Virtual-Social-Physical



# 1 Introduction

This chapter is divided into five sections. First, the background of the research is discussed, highlighting the academic relevance of prosumer driven 3d food printing. The second section indicates the research gap that is existing in this field. Next, scope of this research work is defined. This section describes what areas are covered in this master's thesis, and what are left out. The intended research contribution is also highlighted within this section. The master's thesis timeline is illustrated in the fourth section, whereas the structure of this thesis paper is described in the final section of this chapter.

## 1.1 Background

3d printing (3DP) is one of the most promising and disruptive technological innovation of recent times. It is a manufacturing process that involves layer by layer addition of materials to create 3d products. Due to the nature of the process, it also known as Additive Manufacturing (AM). The whole operation is controlled by a computer program that takes in CAD models in the form of additive manufacturing file format (AMF) or stereolithography file format (STL). AM was originally developed in the early 1980s to fabricate plastic based objects (Mueller, 2012). The technology has evolved over the last three decades, and it is currently able to work with a wide range of materials (Kytannen, 2005; Mueller, 2012; Rayna and Striukova, 2016) including, a variety of natural and synthetic resins, metals, and even food raw materials. Chris Anderson of Wired magazine argues that the potential impact of 3d printing is comparable to the impact that personal computers have had in the field of ICT over the last couple of decades (Anderson, 2012).

Until the onset of 21<sup>st</sup> century, 3d printers were mostly utilized as industrial systems. They began entering the consumer markets with the arrival of open source desktop machines like Fab@Home and RepRap. This has enabled consumers to directly participate in the manufacturing and distribution activities. In other words, desktop 3d printers have enabled prosumption of speciality goods. The term prosumption (Toffler, 1981; Kotler, 1986; Ritzer, Dean and Jurgenson, 2012) here outlines any production activity undertaken by consumers. While desktop 3d printers facilitated prosumption to a certain degree, the creative freedom these machines offered was underutilized. Janne Kytannen described 3d printing at that point as “fascinating technology with little consumer knowledge” (Kytannen, 2005). This has changed since the mainstreaming of digital platforms and web 2.0 (Rayna, Striukova and Darlington, 2015). Increasing level of consumer involvement in the design and production of speciality goods have disrupted the way in which businesses create, deliver, and capture value. This in-turn made the line between production and consumption even thinner.

According to Gartner's hype cycle for emerging technologies, consumer 3d printing is currently at the peak of inflated expectations. The technology is expected to reach a mainstream adaptation level between 2019 and 2024 (Gartner Inc., 2014). This means that its application array is still going to expand in the forthcoming years. Until recently, the idea of printing personalized food was only associated with science fiction series like Star Trek (*Star Trek Replicator*, 1987). However the food production scene is changing fast, and concept designs introduced by MIT (Zoran and Coelho, 2011) and Nestle (Begley, 2014) indicates that real life food replicators are not far away from us. The technology that makes it possible is 3d

food printing. It combines digital gastronomy knowhow with 3d printing technology for producing customized food structures (Sun, Peng, Yan, *et al.*, 2015). After the inception of first 3d food printer prototype at Cornell University in 2007 (Periard *et al.*, 2007; Cohen *et al.*, 2009; Lipton *et al.*, 2010), the academic relevance of the field has grown substantially. According to Frost and Sullivan, the patent trend in 3d food printing has drastically increased over the last few years, with 2014 registering a 550% increase from 2013 (Sullivan and Frost, 2015). The application areas identified for this technology ranges all the way from restaurants to space crafts. NASA’s collaboration with a Texas based enterprise to investigate the prospective of 3d food printing in creating personalized meals for astronauts (Hall, 2013), clearly shows how wide its scope is.

3d food printing is expected to have a far reaching impact on the food value chain, especially on food processing, distribution, and preparation (Gausemeier, Echterhoff and Wall, 2012). It is not only a time and cost saver in producing complex food designs, but also a means to personal well-being. One example is the Performance Project (Bardenstein *et al.*, 2014; Performance, 2015) that developed a personalized and holistic food supply chain for elderly people with swallowing difficulties by making use of cutting-edge 3d food printing technology. This technology also helps in reducing the food wastage, and thereby contributes to the overall sustainability of the value chain (Poutanen *et al.*, 2017). In short, it has the potential to change the way we produce and consume food, like how microwave oven impacted food value chains over the last few decades (see Figure 1).

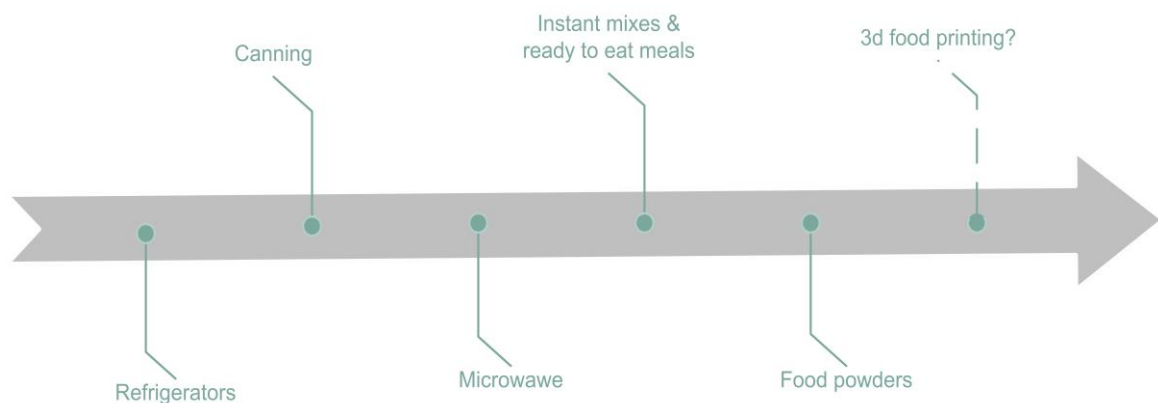


Figure 1: Innovations that changed the way we consume food.

## 1.2 Research gap

Digital platforms are climbing up the Gartner Hype Cycle at a great pace and have become an integral part of present-day consumer experience (Gartner Inc., 2014, 2017). These platforms along with 3d printers and other supplementary assets like IoT, AI, and smart devices have enabled high-level prosumption in the speciality goods sector. Studies conducted by VTT Technical Research Centre of Finland shows that people are anticipating a similar paradigm change in food production scene (Poutanen *et al.*, 2017). Empirical data about the associated change drivers are currently scattered across different academic disciplines. This data is substantial in convincing investors and food enterprises about the central role that 3d food printing could play in our future food system. Since 3d food printing technology is still in its nascent phase, it is also important to understand its constraints and uncertainties. This

knowledge will help engineers and food scientists working on 3d food printing to effectively channel their developmental activities.

Researchers have previously studied the possible interactions between 3d printing, digital platforms and ICTs (Fox, 2014; Rayna, Striukova and Darlington, 2015). But, these studies were mostly focussed on the speciality goods sector. It is doubtful whether the results of such studies hold true for food production sector. In other words, it is still unclear how 3d food printing will go hand in hand with digital platforms and ICTs. Also, a lot of existing use-cases will change or evolve when 3d food printing is integrated with a digital platform. The platform could be a smartphone application that allows prosumers (consumers who produce goods for their own consumption) to design, produce and order personalized food utilizing 3d food printing technology. Identifying potential archetypes and use-cases specifically for such digitally driven 3d food printing systems will help researchers and businesses to innovate mutually beneficial food value chain models. Since these digital platforms are enablers of high-level prosumption, they can also be called as prosumer driven platforms.

All the niches identified in this section can be translated to three research questions (see Table 1).

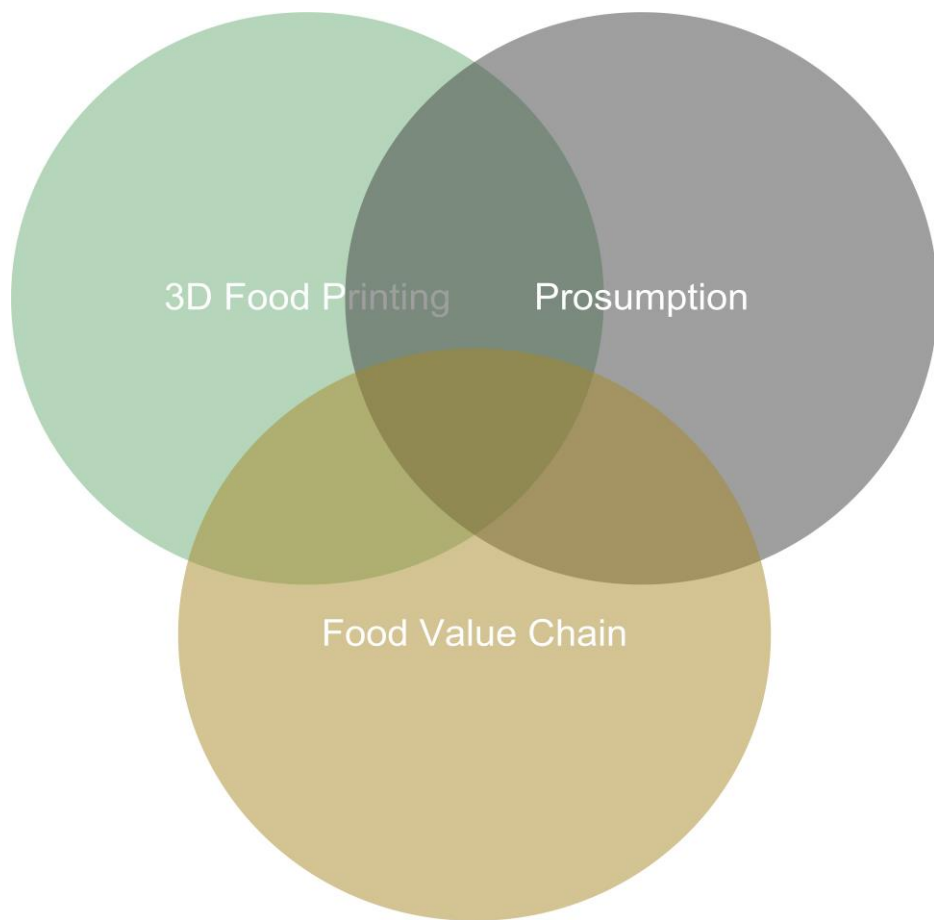
*Table 1: Research questions.*

<b>Research Question 1</b>	What are the change drivers, constraints, and uncertainties of prosumer driven 3d food printing?
<b>Research Question 2</b>	What are the key characteristics, and customization parameters for a prosumer platform for 3d food printing?
<b>Research Question 3</b>	What are the most potential prosumer archetypes, and use-cases for future 3d food printing platforms?

### 1.3 Scope and intended contribution

The master's thesis is composed of three inter-related research themes, namely, food value chain, 3d food printing, and prosumption (see Figure 2). Data collection and analysis is carried out from the perspectives of these three entities. It is to be noted that the scope of this work is limited to prosumer driven 3d food printing platforms as such. This means that while the thesis explores the state of the art of 3d food printing, it is not intended to generate 3d food printer machine concepts or prototypes. Also, this research work is not meant to encompass direct end-user interaction. On the other hand, it follows a user-centric approach to acquire data from experts in the field of 3d printing, food science, and ICT.

The goal of this master's thesis is to create knowledge on how 3d food printing technology can be best utilized by food prosumers. Potential contribution of the associated empirical work is three-fold. Firstly, it provides an updated global state of the art of food system, prosumption, and 3d food printing. It builds-up empirical data about change drivers, challenges, and uncertainties of prosumer driven 3d food printing. Secondly, the research work establishes the nature of a prosumer driven platform for 3d food printing, including its key characteristics and customization parameters. Last but not the least, research identifies plausible archetypes and use-cases for prosumer-driven 3d food printing platforms.



*Figure 2: Research themes.*

## 1.4 Thesis timeline

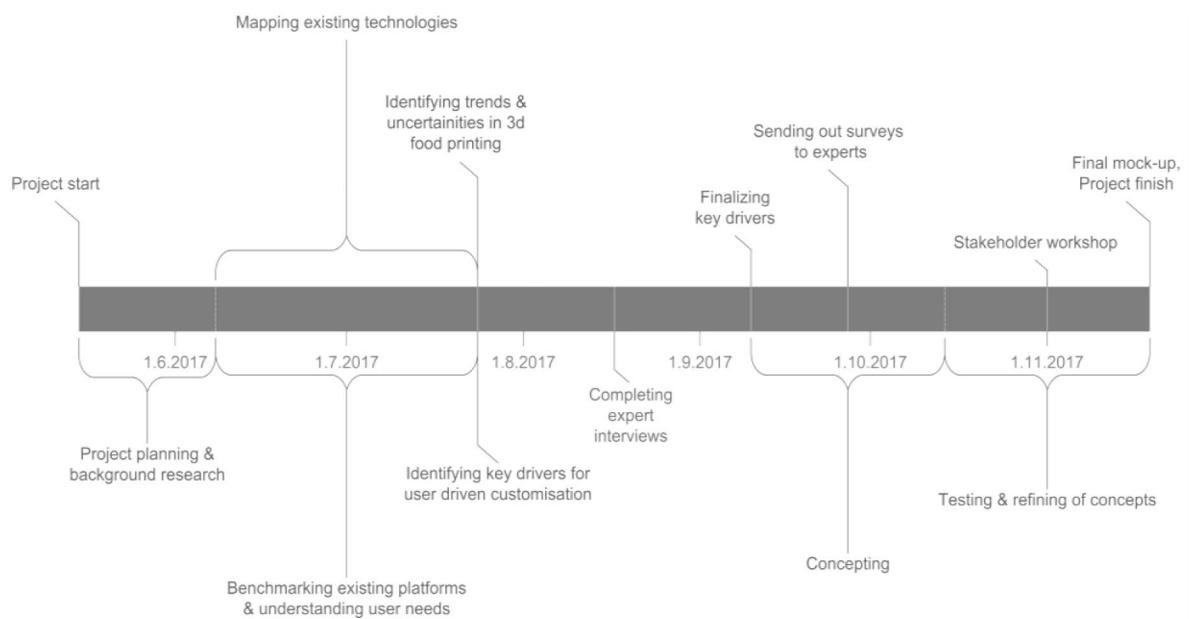


Figure 3: Master's thesis timeline.

## 1.5 Thesis organization

This master's thesis is structured into six chapters. The first chapter is the introduction, which gives background knowledge about the topic in hand, and its relevance. Thesis scope and contribution is also defined in this chapter. The second chapter is theory and state of the art. It explores the current state and predicted developments in food system, the concept of prosumption and its evolution, and 3d food printing ecosystem. The third chapter is research design, where all the methods (expert interviews, expert survey, and stakeholder workshop) and tools (affinity diagram) used in this thesis work are described. The thesis process (modified double-diamond process model) and data collection paradigm (mixed methods research) are also defined in this chapter. Fourth chapter is research findings, which explores the outcome of various research methods and tools used. The fifth chapter is discussion, where the answers to initially identified research questions are summarized along with its implications. The challenges associated with this study and future developmental steps are also discussed. Last chapter of this master's thesis lists out the main conclusions of the research work. References are placed after the sixth chapter. There is also an appendix section in the end that includes interview questions, survey template, workshop charts used, posters of use-cases, and selected quotes from the expert interviews.

## 2 Theory and state of the art

Theory and State of the art chapter of the thesis explores the work that has been done in the areas corresponding to the research themes, namely, the food value chain, prosumption, and 3d food printing. It is divided into five sections. First section of the chapter introduces the traditional food value chain and describes the key elements associated with it. Key trends and developments associated with the food system along with their potential impact are covered in the second section. It describes how the future food system would look like, various alternate ingredients, what are the change drivers, and finally gives a sneak peek to the future of food distribution and consumption. Third section gives a deeper understanding of the phenomenon of prosumption, highlighting how its usage has evolved over the last couple of decades. The impact of ICT developments and 3d printing revolution on prosumption is also discussed. The section ends with a brief explanation of how consumer-centric production could impact the food value chain. The fourth section of the chapter is aimed at giving an all-round understanding of 3d food printing to the reader. The technologies that could be used for 3d printing food, along with the associated ingredient portfolio are discussed. The section also highlights the significance of this innovation for consumers and businesses. Market segmentation and the potential reach of 3d food printing is also touched upon. Fifth section is all about the present ecosystem for 3d food printing, covering the existing value chains and state of the art concept designs.

### 2.1 The food value chain

The food value chain represents the network of all the actors and their value adding activities involved in various stages of the food life cycle. These value adding activities range from research, and production of ingredients to consumption and waste management (Kaplinsky and Morris, 2000). Figure 4 represents a traditional food value chain in its simplest form. It starts with the production of food ingredients. These ingredients are then distributed to food processing brands. These are enterprises that convert raw ingredients to palatable food, or already consumable food materials into different forms that can easily be marketed. It is done either by chemical or physical means, often combining different ingredients. Various preservation processes like refrigeration, freezing, canning, irradiation, dehydration, pasteurizing etc. are also considered and carried out at this stage. Packaging is another important aspect that is often taken care of by food enterprises once the processing activities are completed. Processed and packaged food ingredients, or ready to eat food products are then distributed to different food vendors. These food vendors range from large supermarkets, and restaurants to smaller groceries, bakeries, and cafés. Figure 4 shows two different distribution paths between food processing and consumption. In the first case, consumer buys ready to eat food products or ready to cook food ingredients from supermarkets or groceries, which are later consumed at home. Second case involves buying and consumption of food products at a restaurant or café. First case may involve some extra processing or cooking process from the consumer's part, while the second case is devoid of any such extra steps.

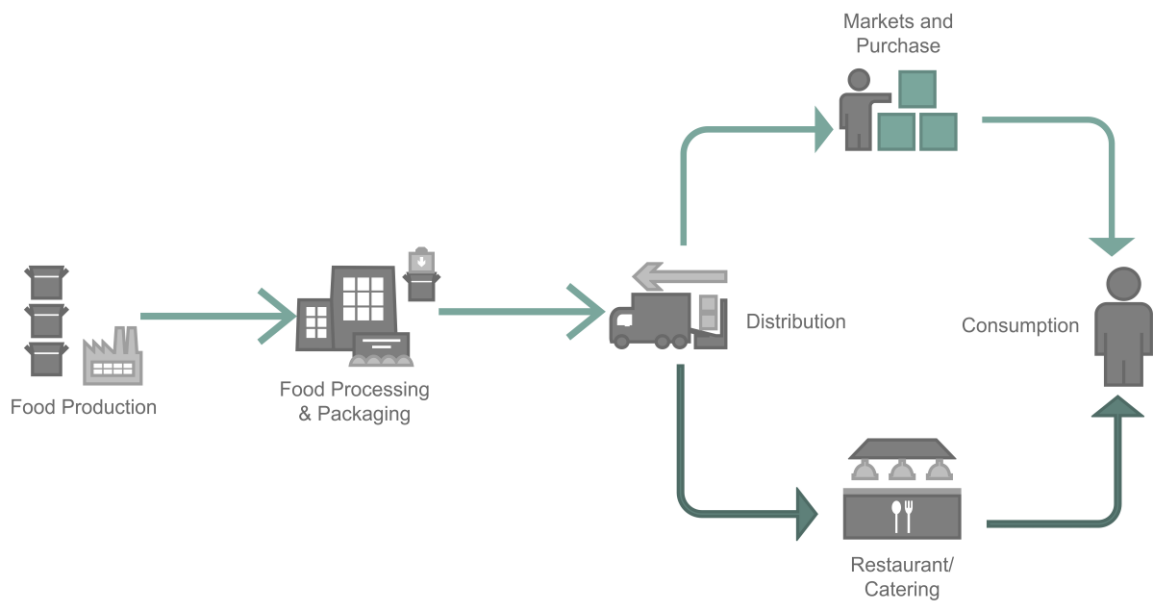


Figure 4: A simple food value chain.

In fact, food value chains are not as simple as the one represented in Figure 4. They constitute a lot more actors, and hence involve more links and distribution paths (Kaplinsky and Morris, 2000). Figure 5 represents such an extended form of the value chain. Here, the value creation starts with primary production of food ingredients and ends with waste management. Many food ingredient producers and processing brands started using services from research agencies and consultancies. With digitalization and advancements in processing technologies, role of software and hardware providers, and service agencies have become more central to the value chain. Food brands have also realized the importance of packaging, and often collaborates with design agencies and packaging consultancies for creating a better package experience for consumers. Globalization and digitalization has changed the way how marketing is done. Marketing is now a core activity in the value creation process, and many food enterprises seek help from external firms for market research, branding, go to market planning, and internationalization.

Much of the distribution channel, i.e., the transactions between different actors in the value chain, has been digitized. A new category of business model called e-commerce has disrupted the distribution channel. With digitalization and e-commerce models, a significant amount of the monetary transactions is carried out over the internet. Many global retailers now have online stores, where consumers can place orders and pay for the goods irrespective of their location. These changes have direct implications on warehouse management and optimization of distribution channels. E-commerce is a general trend, but is very visible in the food sector (FAO, 2017; Poutanen *et al.*, 2017). E-commerce and digitalization has not only impacted food markets and retail outlets, but also the restaurant businesses. ‘Digital food delivery’ doesn’t just mean ordering of food from a restaurant over internet anymore. It is about providing a food experience close to that one gets at a regular restaurant, but without a physical eating space. ‘Epic Foods’ based in Helsinki, ‘Foodora’ based in Berlin, ‘Just Eat’ & ‘Deliveroo’ based in London are some examples of such a digital food delivery service. Packaging, sustainability, and bringing in surprise elements with meals are critical to such digital business models in food industry.

Value chain represented in Figure 5 ends with waste management, which is critical in the overall sustainability of food system (Godfray *et al.*, 2010; FAO, 2017). It is taken care of by consumers in case of home consumption, and otherwise by restaurant businesses or food outlets. It is a major concern in the food system at present, whereas there is also a huge scope for innovation associated with it. Many players in the food industry have already realized the importance of tackling this challenge. One example is ‘ResQ Club’, a start-up in Helsinki that allows consumers to order leftover food from different restaurants in the city through a smartphone application.

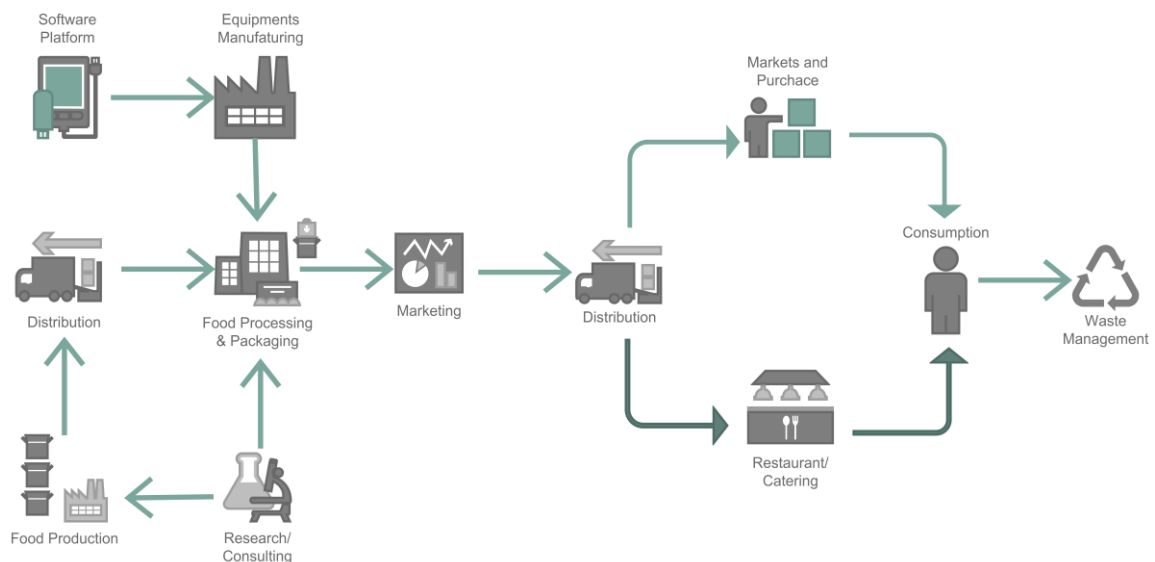


Figure 5: An extended food value chain.

One of the most significant 20<sup>th</sup> century innovation in food processing sector is mass standardization, i.e., creating tastes and textures that remains uniform throughout the world, at any time of the year. This often involves adding of additives, and shipping pre-processed food from one part of the world to another. It also involves a lot of air miles, adding to the carbon footprint and food wastage due to spoilage. Consumer desirability for such standardized food is slowly diminishing. Also with globalization, the food supply chain has grown to be very complex and less transparent. Food economy 3.0 (Poutanen *et al.*, 2017), characterised by industrial mass production of food, has also led to heavy centralization of food and retail sector.

A continuous increase in the demand for fresh and locally produced food ingredients has been predicted (FAO, 2017; Poutanen *et al.*, 2017). This trend along with the advancements in ICT and manufacturing technologies could lead to a shift from mass standardization to mass customization in food production and marketing. VTT Technical Research Centre of Finland calls this revolution as Food Economy 4.0 (Poutanen *et al.*, 2017). This version of food economy will be characterised by smart production of food utilizing opportunities created by cyber-physical systems. Much of the production and processing will be localized, potentially leading to minimal use of food additives, and opens-up opportunities for personalized nutrition. All these would in-turn make the industry more transparent, while reducing packaging needs and food miles. Most importantly, it will help in facilitating a better bonding between people and the food they consume (Avery *et al.*, 2014; Chesney, 2014).



Even with all the favourable trends and possibilities, innovations in the food sector has a success rate of only 12-28% (Stewart-Knox and Mitchell, 2003), particularly in consumer level food-tech start-ups (Smith, 2013). This low success rate is despite the huge market potential for such innovations. For the food-tech innovations to be adopted widely in the market, a change in consumer behaviour is prerequisite. This is where many businesses face a challenge, as consumers usually tend to stick on to their traditional eating habits. In addition to this, technology oriented food production often creates a wrong impression among consumers; for example, any kind of food processing sounds artificial to a lot of people (Smith, 2013). Many psychological barriers can be dealt with good marketing activities. Involving consumers in the value creation process is the best way to go, as it would change how they view food, food production, and food processing. Brittany Smith of Wired magazine points out that venture capital firms and entrepreneurs should focus on the food production value chain holistically during the innovation process. This would help in creating a food system that is mutually beneficial to the food producers, consumers, and the environment. Also, early stage investments in food-tech research from large food brands, venture capital firms, universities, and other scientific research communities would ensure a long-term positive impact on food system, disrupting the food experience (Smith, 2013; Chesney, 2014).

Food industry is vulnerable to rapid overcrowding, creating challenges in product differentiation. Because of this reason, the success rate in food product development is generally low. Food product development refers either to the development of an original and unique food product, or refining of an existing product. The success rate for the former is found to be much higher than the latter, given that the identified consumer needs are satisfied (Stewart-Knox and Mitchell, 2003). To tackle the challenge of product differentiation, food brands should take measures right from the beginning of the concept development process. Such measures may include seeking outside support in the form of consultations with market research firms and consumers. Understanding the market conditions and consumer needs prior to the food product development process will reduce the chances for failure at market entry. This will also help in identifying market niches for the new product ideas (Stewart-Knox and Mitchell, 2003).

## **2.2 Future of food**

Future of food is not just dependent on technology, but also on changing societal behaviour of consumers, government policies and most importantly the changing societal way of thinking. According to UN FAO, global demand for food will have a 70% rise by the year 2050 (FAO, 2017). There are several drivers that contribute to this steep rise, most important of which is the growing global population. UN projects the world population to touch 10 billion mark by 2050 (FAO, 2017). With such a growth in population, there will be an obvious increase in food consumption. Economic growth of developing countries and changing income distribution are two other trends that will lead to an increase in the food demand globally (FAO, 2017) (Godfray *et al.*, 2010). Income growth directly leads to a change in consumption pattern, especially in low-income and middle-income countries. Those economies would see a dietary transition towards nutrient rich meals including meat, from a mostly-cereal based diet. Change in consumption pattern and population growth in the food-insecure regions of the world should be addressed by having a resilient food system. If not, it would lead to an over exploitation of natural resources; loss of bio-diversity through de-forestation and land degradation; and increase in the emission of harmful greenhouse gases (Godfray *et*

*al.*, 2010; FAO, 2017). This will have serious repercussions on the environment, adding on to the ongoing phenomenon of global climate change.

The trends identified above, namely growing food demand and change in consumption pattern (Godfray *et al.*, 2010; FAO, 2017), underlines the importance of timely investments in research towards a sustainable food system, by exploiting the emerging technologies in both manufacturing and ICT. The focus should not only be on feeding the growing population with nutrient rich food, but also to prevent over exploitation of natural resources. According to Rebecca Chesney, the Research Director of Food Futures Lab at the Institute for the Future (IFF), food related research activities are not confined to food science and nutrition anymore, but have opened-up to encompass sustainable food systems, culinary diplomacy, and food anthropology (Chesney, 2014).

### **2.2.1 Future of food production**

A research avenue that is very relevant considering the rising food demand and climatic change is the quest towards alternate food ingredients (Poutanen *et al.*, 2017). The carbon footprint being generated by the meat production industries and resource intensive agriculture (Avery *et al.*, 2014) is alarming, as it is impacting global warming directly (Poel, 2016). Big players in the food production value chain, as well as many research organizations are already working towards smarter and more sustainable means of producing nutritional foods. It is also important to keep an open mind regarding food diversity, considering the growing population and changing consumption patterns in different parts of the world (Poel, 2016; Poutanen *et al.*, 2017).

Bas van de Poel, the head of playful research at Space10, stresses on the importance of incorporating alternate food ingredients to our daily meals. According to him, this would help the people in preparing themselves to an inevitable change in eating habits (Poel, 2016). Space10, in collaboration with Ikea, envisioned the future of food with various alternate ingredients, by keeping emerging technologies in mind. From a feasibility and viability point of view, artificial meat (Bonny *et al.*, 2015; Poel, 2016) is one such option for the future protein needs. It is produced through cell culturing using latest technologies in tissue engineering (Bonny *et al.*, 2015). Because of the production means, artificial meat is also known as cultured meat. Even though it has the potential to replace regular meat, the consumer desirability of such lab-grown meat is still a question to be pondered on. Insect protein is another alternative ingredient that has already proved to be economically viable. Insect farming is a highly sustainable business as it takes up comparatively less space, and needs only a limited supply of food and water. The food conversion efficiency of insects is around 20 times more than that of traditionally produced meats (Soares, 2011; Smith, 2013; Poel, 2016). Also, nutritional content of many bugs, especially protein, iron, and calcium content are much higher than commercially available red-meats. They are also a much healthier food source due to the low saturated fat content. While bugs are already consumed by 80% of the world nations (Smith, 2013; Poel, 2016) in one way or the other, its commercial availability is restricted in many countries by food legislative frameworks. These legislatures are expected to change soon, making insect protein a very reliable alternative ingredient. Insect based food processing businesses should incorporate good marketing activities to convince consumers that it is a safe, healthy, and sustainable food source.

Powder and liquid based meals are becoming increasingly popular as the nutrients to weight ratio in such diets are much higher compared to conventional meals. These nutrient rich powders and liquids can condense a variety of macro-nutrients and micro-nutrients in them, which opens-up opportunities to utilize them in tackling issues related to malnutrition and food security. Algae (Poel, 2016) is another alternative food ingredient which is rich in vitamins, minerals, and proteins. It is a scalable food source that can be grown almost anywhere. For people with dietary restrictions, vegans for example, algae based meals are an option to consider in the near-future. UN estimates around one-third of the total food being produced globally is going to waste (FAO, 2017). Food security is a major global challenge, and it should be tackled by minimizing food wastage. One plausible solution according to Space10 is to incorporate leftover ingredients from food production and processing into our gastronomy (Poel, 2016). A major trend in the present-day food production is urban farming (Godfray *et al.*, 2010; Poel, 2016; FAO, 2017), as people are increasingly preferring locally grown food ingredients. This trend would directly lead to more employment opportunities, strengthens bio-diversity, and makes the food supply chain much more transparent. Growing food ingredients locally reduces the carbon foot-print associated with transportation, and makes the food system more resilient to global climate change (Godfray *et al.*, 2010; Poel, 2016; FAO, 2017).



Figure 6: Future meatballs made from alternate ingredients (Poel, 2016).

### 2.2.2 Future of food distribution and consumption

Future food will not just be a source of nutrition, but also a means to personal wellbeing. Fostering a personalized food experience is what the food enterprises are striving for. The way in which we shop food, and how we consume it is changing gradually. There will be a shift from centralized shopping of food to just in time delivery (Poutanen *et al.*, 2017). IoT and advancements in machine learning will enable decision free ordering of food, while disruptive distribution services like drone delivery and use of autonomous vehicles ensures that

fresh food supplies reach the consumer automatically when in demand. A lot of shopping in the future will be done virtually, irrespective of the customer location. Technological advancements also allow food orders to be determined from consumer eating habits and medical data.

VTT Technical Research Centre of Finland predicts that next generation food vending machines combined with the latest production technologies will enable easy customization and distribution of food products based on individual needs (Poutanen *et al.*, 2017). This will not only help in disrupting the food value chains, but also improves the overall consumer well-being. Entrepreneurs have already realised the potential of smart food vending and the role it could play in the market for food service robots. Markets and Markets forecasted that by 2022, the global market for service robotics will reach around 24 Billion USD (MarketsandMarkets, 2017). New players like Chowbotics Inc. (Chowbotics Inc., 2017; Krader, 2017) are already leveraging this market potential by utilizing the latest food vending technology. Sally, the salad robot by Chowbotics can prepare and deliver customized, fresh, and healthy salads made of ingredients selected by a professional chef. Sally could take in 21 ingredient canisters and prepares a 7-component salad within a minute. Consumers can watch the salad being prepared, and can monitor the total calories. The system is refrigerated and hence the ingredients will stay fresh for extended time periods. On the flip-side, the salad ingredients must be cut and pre-processed manually before being filled into the canisters. More players like Chowbotics are likely to hit the market in the coming years, since a CAGR of 15.18% is expected in the service robotics market (MarketsandMarkets, 2017) between 2016 and 2022.

Along with convenience, satisfaction in eating is also a significant driver for change in the food sector (Poutanen *et al.*, 2017). A healthy meal doesn't always imply that it's delicious and desirable to the consumer. A healthy, but blunt meal can be made a lot more enjoyable by hacking and manipulating human senses utilizing technology (Avery *et al.*, 2014). A combination of AI and VR could help recreating nostalgic meal experiences, with continuous monitoring of consumer preferences. This could bring an added value, for example, in the case of in-flight dining and hospital meals.

### **2.3 The era of prosumers**

Alvin Toffler introduced the term prosumer in his book 'The Third Wave'(Toffler, 1981). Prosumer refers to people who actively produce goods and services for their own consumption. Even though the term was introduced in the early eighties, the concept of prosumer existed very much before that (Toffler, 1981; Kotler, 1986; Ritzer, Dean and Jurgenson, 2012). Karl Marx, while regarded as the supreme savant of industrial production, realized that people often took turns in their roles as producers and consumers. Marx also understood the potential impact of this interplay long before Toffler.

Toffler in his book argues that prosumption or prosumerism, which is the amalgamation of production and consumption, is not a new phenomenon, but existed predominantly in the pre-industrial era. Toffler's work (Toffler, 1981) points out the interrelation of production and consumption through the 3 eras of human history, i.e., pre-industrial, industrial, and post-industrial (see Figure 7). His work was further expanded by Philip Kotler (Kotler, 1986), who underlined the difference between production for exchanging and production for

using. Toffler called the pre-industrial era as the ‘First Wave’ (Toffler, 1981) of human history, where the economy was largely dependent on agricultural activities. Most of the people in this age were prosumers, since they grew crops for their own consumption for example. A small section of the society did specialized trades like fishing, carpentry, and black-smithing. They exchanged their competency for goods, such as grains and clothes, produced by the larger section of the society. This small section were the consumers of the pre-industrial age (Kotler, 1986). The ‘Second Wave’ (Toffler, 1981) of human history is associated with the industrial revolution, which gave rise to pure consumers and producers. With the outset of factories, people began producing goods solely for exchange. This led to the marginalization of prosumer population and a sharp increase in consumer population within the society. Majority of the existing prosumers engaged in un-paid household chores like cooking, cleaning, and knitting (Kotler, 1986). Even during the era of industrial revolution, the role of producers and consumers were not completely distinct (Ritzer and Jurgenson, 2010) since consumers produced meals for themselves and producers consumed goods made at the factories.

Toffler and Kotler (Toffler, 1981; Kotler, 1986) were quite ahead of their times when they predicted that the society will move towards an age of individualization from that of mass consumption. Toffler called this post-industrial age as ‘The Third Wave’ of human history (Toffler, 1981), where he predicted a gradual decline of pure consumers. Since increasingly people start producing goods for themselves, the size of prosumer population will continue to increase relative to that of the consumers. More people in the post-industrial era are getting high level education compared to that in the industrial era. This along with all the advancements in technology leads to a decrease in the acceptance rate of boring and repetitive tasks. There is also a gradual decline in the working hours, and a trend towards working smart instead of working hard. This has made skilled labour more expensive to hire. Hence, instead of seeking outside expertise, people with the help of available technology, are taking care of not-so-complicated service tasks. In case of goods, people increasingly want personalization, and many a time feel that they themselves can produce better quality goods. All these changes (Toffler, 1981; Kotler, 1986) are drivers for demassification and waning market dependency in general, thereby fuelling prosumer activities.



*Figure 7: Three waves in human history according to Alvin Toffler.*

With the rise of prosumers, the demand for mass produced goods and services will continue to decrease. Also, consumers become less brand conscious while purchasing goods and services. This according to Kotler (Kotler, 1986), is a serious marketing challenge for enterprises. Marketing activities of firms should focus on finding what prosumer activities are most likely to happen. Kotler argues that an ideal prosumer activity requires very little skill, saves cost, demands minimal time and effort, at the same time delivers high personal contentment (Kotler, 1986). An example given by Kotler for an ideal prosumer activity is house painting. Identifying such activities at the right time will open-up value adding opportunities for enterprises. Instead of competing with prosumers, they should help facilitate prosumption. Salad buffet in restaurants is one example that shows how enterprises can leverage

prosumption in value creation. It satisfies people's desire to participate in the production process, at the same time brings in value for the business.

21<sup>st</sup> century is an age of collaboration, and not competition. Firms are joining hands with each other for creating mutually beneficial output. Additionally, prosumers will play a significant role in this mutual value creation, and the latest ICT advancements will assist them in doing so (Prahalad and Ramaswamy, 2004; Tapscott and Williams, 2006). With prosumers gaining centrality in the value chain, businesses should rethink their value adding strategies. For instance, distributors and retailers only require minimal inventories, and hence minimal warehouse space. Also, firm's branding and marketing activities should focus more on themes like production efficiency, personalization, and skill development (Kotler, 1986). In short, prosumers according to Kotler should be treated as a separate market segment (Kotler, 1986).

### 2.3.1 Evolution of prosumption

Even though the term prosumption was formalized in the early eighties, the phenomenon remained under-researched until the start of 21<sup>st</sup> century. The surge of prosumption related research activities that we are currently witnessing is mainly due to the societal changes (Ritzer, Dean and Jurgenson, 2012) associated with advancements in ICT such as web 2.0 (Beer and Burrows, 2010), and technology innovations like 3d printing (Rayna, Striukova and Darlington, 2015). These advancements are making value creation process more user-inclusive (Prahalad and Ramaswamy, 2004; Tapscott and Williams, 2006), thereby expanding the scope of prosumer activities.

Rayna, Striukova and Darlington has categorized prosumer activities into three major groups (see Table 2), namely, blue collar prosumption, white collar prosumption and prosumption through investment (Rayna, Striukova and Darlington, 2015). Early prosumption activities were mostly limited to blue collar DIY tasks (Toffler, 1981) such as constructing and painting one's own house, cooking food and making clothes for oneself. With the arrival of computers, internet and IT platforms, prosumption has evolved to incorporate various customization activities. This type of white collar prosumption is very much evident in the automotive market for example. The emergence of e-commerce market has also boosted white collar prosumption by providing similar mass-customization possibilities. The third type of prosumption happens when consumers invest in software, and devices like computers, printers, scanners, and cameras; in order to co-design and manufacture at home (Tapscott and Williams, 2006). These equipments that the consumers invest on are complementary assets for businesses, are critical in their value creation, value delivery and value capturing. It is also interesting to note that the third prosumption type is often a combination of the first two types.

*Table 2: Three types of prosumption (Rayna, Striukova and Darlington, 2015).*

<b>Prosumer type</b>	<b>Prosumer activity example</b>
Blue collar prosumer	DIY activities like house painting
White collar prosumer	Customized product orders
Prosumer as investor	Printing or scanning from home

As mentioned earlier, more companies continue to recognize the significant role that prosumers could play in the business innovation process. Working together with prosumers allows them to leverage value creation with user desirability, hence minimizing the chances of failure at market entry. With value co-creation gaining more prominence on an industrial scale, companies are considering prosumers for more active and creative roles than before (Pralhad and Ramaswamy, 2004). Latest ICT infrastructure with enhanced connectivity and access to information, ensures their effortless participation in idea generation, design and development, manufacturing, testing, as well as distribution activities. In short, prosumers now have a more central role in the value chain, rather than just being workforce replacement in the manufacturing processes.

Marketing activities, especially in the developed world, are undergoing an inevitable transition towards Service Dominant (SD) logic (Lusch, Vargo and Wessels, 2008) and Customer Dominant (CD) logic (Heinonen *et al.*, 2010), from the traditional Goods Dominant (GD) logic. This break-away from GD logic was predicted long ago by Toffler and Kotler in their works (Toffler, 1981; Kotler, 1986) related to prosumption. With this transition, a service is not just an output anymore, but a collaborative process between producers and consumers that finally results in mutual value. SD logic and CD logic, being two close attributes of prosumption, allows businesses to gain totally new perspectives to value creation (Heinonen *et al.*, 2010). The high level of user involvement associated with these marketing logics has softened the line between production and consumption, thereby minimizing the gap between products, services, and user environments.

### **2.3.2 Prosumer driven 3d printing: A new manufacturing paradigm**

As discussed in the previous section, ICT advancements over the last couple of decades have greatly boosted up prosumption activities. These digital developments when coupled with additive manufacturing (AM) technology, have the power to take the prosumer activities to a whole new level. AM is predicted to be most transformative during the 2015 – 2025 period, and is expected to further disrupt the existing manufacturing paradigm (Karlgaard, 2011).

Production processes in general are comprised of three critical activities, namely, designing, manufacturing and delivery (Rayna, Striukova and Darlington, 2015). Initially, prosumer involvement was limited to the manufacturing and distribution stage, desktop 3d printers being the enabler. With the emergence of online 3DP platforms, prosumers started contributing to the design process, sometimes even taking a leading role. In short, these online platforms gave prosumers a more central role in the 3DP business, enabling them to intervene during any stage of the production process. This kind of co-creation process often results in experience innovation (IDEO, 2009), i.e., the creation of products and services that are not only technologically feasible and economically viable, but also desirable to the end-users.

Many enterprises in the present-day market outsource production to other independent companies, without launching a new production unit of their own. Such models help generating mutually beneficial outcomes for the businesses and consumers (Hedstrom, 2016). It allows businesses to fully concentrate on their core competence, while maintaining a strong collaboration with consumers and other actors of the value chain. The main value in this case comes with the production of products in large batches (high volume) with minimal or no

variation. But with a prosumer driven 3DP platform, such businesses could also offer customers the interesting possibility of product personalization. Prosumer driven 3DP services won't replace the traditional manufacturing completely, but helps businesses in reducing the time for production and the total costs involved, while keeping customers happy (Hedstrom, 2016). One interesting possibility of 3DP is to utilize its novelty value in creating a marketing story for a totally new product or an add-on to an existing product (Jiang, Kleer and Piller, 2017). The novelty value of 3DP will also help enterprises in creating new sales channels, and reaching new markets with reduced efforts.

As new business models continue to emerge in the fast growing 3DP sector, questions regarding the overall sustainability of the process is very usual. Scholars (Gebler, Schoot Uiterkamp and Visser, 2014) have found that AM possess a very high sustainability potential, since it reduces resource intake and energy utilization considerably. The technology helps shifting factory centric production towards localized manufacturing, with the support of digital platforms. This results in a simplified supply chain with lower overall emissions. Unlike conventional manufacturing techniques, AM is a one step process. It facilitates mass customization, makes low volume production economical, and potentially disrupts the manufacturing distribution chain. The process doesn't require any special tools, moulds, or labour, hence reduces the overall manufacturing costs. AM is a versatile process that allows multiple product variations in the market at the same time. This minimizes competition, and enables easy-market entry. The latter is also due to the minimal capital costs associated with the process (Weller, Kleer and Piller, 2015).

### **2.3.3 Enablers of future prosumption**

The mainstream prominence gained by prosumption, with the emergence of ICT innovations like computers, internet, software platforms and web 2.0, is further cemented by the prosumer driven 3DP revolution. Its role in the specialized goods market has expanded drastically over the last decade. Scholars (Ritzer and Jurgenson, 2010; Rayna, Striukova and Darlington, 2015) points out that the inter-relationships between prosumption, web 2.0, and innovations like 3DP are dynamic, and will continue to change in the up-coming years. Future ICT and production technologies will not only allow people to express themselves in a better way, but also facilitates the creation of a digital identity they desire. In other words, it fosters creativity and hence more original product ideas.

Over the last few decades, large-scale manufacturing paradigms have changed much evidently. Production of standardized goods on a substantial scale become less relevant with the arrival of mass customization. Stephen Fox of VTT Technical Research Centre of Finland argues that the creation of completely unique and original goods could become the paradigm for large-scale manufacturing in the future. This could be made possible by combining web 2.0 platforms like blogs and social media, with virtual design tools and digitally driven additive manufacturing, which he termed as Virtual-Social-Physical (VSP) convergence (Fox, 2014). This not only unleashes consumer creativity, but also takes away the need for product pre-designs in manufacturing. People without design skills can utilize technologies like digital scanning and photogrammetry to convert a rough 2d sketches to manufacturable 3d models. Smart pens, that are currently available in the market, allows for the real-time conversion of paper sketches into digital model. VSP convergence could potentially play an impactful role in developing countries, as it minimizes the need for industrial skills and manufacturing infrastructure (Fox, 2014).



Stephen Fox further argues that the scope of human self-expression and creativity, associated with the prosumption of unique and original goods, can be expanded of the applications of Artificial Intelligence (AI). AI when combined with virtual technologies and digital manufacturing, will offer an increased level of convenience and choice for prosumers (Fox, 2016, 2017). Present boom in big data and a wider adoption of complementary technologies like Internet of Things (IoT), is leading to a movement called lifelogging or quantified self (Sharon and Zandbergen, 2016). It combines wearable sensors with wearable computers or smart phones, enabling self-tracking of almost all the essential aspects of a personal life. These aspects may include sleep, diet, activities, physical and mental states, as well as the quality of surrounding environment. The collected data can be used in the prosumption process, improving functionality of the resulting products. These futuristic innovations not only help in expanding the scope of prosumption, but also adds-in a gamification aspect to it.

## 2.4 3d printing of food

3d food printing, technically referred as Additive Food Manufacturing (AFM) (Pinna *et al.*, 2016) or Food Layered Manufacturing (FLM) (Wegrzyn, Golding and Archer, 2012), is a collective term for a variety of technologies that enable layer by layer construction of food structures from a 3d model. This food fabrication technique requires comparatively less human interference, but at the same time provides a variety of customization possibilities. Native software present in 3d food printers accepts food structure designs in the form of STL file format or AMF. Printer itself consists of a 3 axis (XYZ) cartesian coordinate system with a material feeding or sintering unit. In most cases, a GUI is also present to manipulate printing parameters like deposition rate and geometry (Sun, Peng, Yan, *et al.*, 2015; Sun, Peng, Zhou, *et al.*, 2015). The process is completely different from that of food robots, which just automates the traditional cooking process. 3d food printers on the other hand helps translating unique food designs in to individualized edible structures (Wegrzyn, Golding and Archer, 2012). In fact, food printing is a truly interdisciplinary field that connects advanced production technologies with food science and ICT. Due to this reason, it has the potential to bring-in a high degree of prosumption within the food system.

The process flow of 3d food printing is slightly different from that of the conventional AM process, considering the nature of print material. Four core steps has to be present in the process, in order for it to impart real functional value (see Figure 8) (Zoran and Coelho, 2011; Sun, Peng, Yan, *et al.*, 2015; Sun, Peng, Zhou, *et al.*, 2015). First step is termed as ‘metering’, where food design, texture and composition are optimized based on user preferences. Second step involves mixing of food ingredients. This step is very important since most food products are composed of multiple materials with complex internal structures (Lipton *et al.*, 2010; Millen, 2012). In a lot of cases, a pre-processing step is also involved. Third step is where the actual layer by layer deposition/ sintering of ingredients takes place. It can be termed as ‘dispensing’. Final step is cooking or post-processing (e.g., heating or cooling). This is often necessary since a lot of food ingredients require some sort of chemical reaction to be completely palatable. Also, varying heat penetration levels associated with it contributes to the formation of a non-homogeneous food texture (Sun, Zhou, *et al.*, 2015). The pre-processing step in the beginning of the process helps in maintaining geometric stability after dispensing process, and nutritional stability during post-processing operations

(Sun, Peng, Yan, *et al.*, 2015). It should be noted that the first two functions are rather challenging to implement, considering the complex rheological characteristics of food ingredients.



Figure 8: Four steps of AFM (Zoran and Coelho, 2011; Sun, Peng, Yan, *et al.*, 2015).

It is to be noted that 3d printing of food is comparatively a new development in the AM sector. Even though the first patent was filed in 2001 by Nanotek Instruments Inc. (Yang, Wu and Liu, 2001), no functional prototypes were made until 2007. Research and development activities related to 3d food printing gained momentum with the mainstreaming of digital manufacturing technologies and desktop 3d printers (Sun, Peng, Yan, *et al.*, 2015). The field is experiencing quick changes ever since, and many of the concept designs that were considered unrealistic are currently on the verge of being implemented. Initially, the application portfolio was limited to creating complex shapes with naturally printable food raw materials like sugar, hummus, chocolate, and cheese (Yang, Wu and Liu, 2001; Periard *et al.*, 2007). This has evolved to incorporate the creation of personalized recipes with traditional food ingredients like rice, meat, fruits and vegetables (Lipton *et al.*, 2010; Tanaka *et al.*, 2015). Current research is focussed on creating fully personalized food textures with healthier (Lille *et al.*, 2017), and more sustainable food ingredients (Soares, 2011; Holland *et al.*, 2016). On the other hand, it is difficult to predict the mainstream market acceptance of emerging 3d food printing concepts (Izdebska and Zolek-Tryznowska, 2016), since the technology is still being refined and potential value chains are still under investigation.

#### 2.4.1 Ingredient portfolio for 3d food printing

3D printing is still an emerging technology with regards to food applications, and some of the biggest challenges associated with it are related to the selection and optimization of ingredients. Ingredient choice for 3d food printing will also have a considerable impact on mixing efficiency, printing speed, geometric accuracy, and compatibility with conventional post-processing techniques. Food ingredients that can be utilized by the existing systems for food printing are classified into 3 groups, i.e., natively printable food ingredients, traditional non-printable food ingredients, and alternate food ingredients (Sun, Peng, Yan, *et al.*, 2015; Sun, Peng, Zhou, *et al.*, 2015; Sun, Zhou, *et al.*, 2015; Izdebska and Zolek-Tryznowska, 2016; Pinna *et al.*, 2016).

**Natively printable food ingredients** can be sub-divided in to two groups- natively printable food ingredients that exists in paste-like forms and the ones in powdered forms (Yang, Wu and Liu, 2001; Periard *et al.*, 2007). The former includes chocolate pastes, hummus, mashed potatoes, batter, pasta dough, cheese, icing and hydrogel; while sugar and starch falls under the latter group. Natively printable materials are comparatively easier to mix, and personalize for texture, flavour, and nutrition. They seldom require post-processing operations and therefore find applications in the health and well-being sector, and confectionery businesses. Some of the materials like batters (Millen, 2012) require compulsory post-processing for retaining nutritional value and taste.

**Traditional non-printable food ingredients** include rice, meat, fruits, and vegetables. Such materials can be made printable by adding hydrocolloids or other simple additives (Cohen *et al.*, 2009; Lipton *et al.*, 2010; Sun, Peng, Yan, *et al.*, 2015; Godoi, Prakash and Bhandari, 2016; Izdebska and Zolek-Tryznowska, 2016). In Asian countries, rice is a staple food ingredient and has very high demand. Japanese scholars (Tanaka *et al.*, 2015) have carried out printing trials by mixing rice powder with a small portion of water. Since rice paste is non-edible, printed structure should be heated in an oven.

**Alternate food ingredients** like protein from algae and insects has the potential to tackle the global food security challenge. Texture and mouth feel of food printed with such ingredients can considerably improve consumer desirability (Izdebska and Zolek-Tryznowska, 2016). They can also be mixed with natively printable ingredients like cheese and icing for creating tasty food structures, as demonstrated in the “Insect Au Gratin” project (Soares, 2011). Another interesting alternate ingredient option is cellulose, which is the most abundant organic polymer in world. Researchers have found that the food grade powders of semi-crystalline cellulose can be used in creating 3d printed food structures (Holland *et al.*, 2016). Professors Oded Shoseyov and Ido Braslavsky of Hebrew University in Jerusalem have developed an AFM technology, which is capable of printing entire meals using nano-cellulose. Cellulose is all natural, healthy, and highly sustainable. This easily digestible ingredient with zero calories is used together with other nutrient rich raw materials. Nano-cellulose binds together the raw materials on application of heat from a laser source, creating warm and healthy meals (Benedict, 2017). VTT Technical Research Centre of Finland has also examined the rheological characteristics of healthy and sustainable food ingredients like cellulose nano-fibre, proteins from broad beans and oats (Lille *et al.*, 2017).

For creating high quality 3d printed food structures, ingredients should possess three important traits. These includes the ability to hold its shape after the deposition process; ability to customize nutritional content, texture and shape to a high degree; ability to maintain geometric and nutritional stability during and after post processing operations (Godoi, Prakash and Bhandari, 2016; Pinna *et al.*, 2016).

### 2.4.2 3d food printing technologies

Matching food ingredients with suitable 3DP technologies is one of the most difficult task in the field of 3d food printing now (Godoi, Prakash and Bhandari, 2016; Pinna *et al.*, 2016). Each of the currently available 3DP technologies are based on distinct working principles that utilize different materials. Standards formulated by “ASTM F42 – Additive Manufacturing” committee has categorized these technologies into 7 clusters (ASTM-International, 2015), namely sheet lamination, VAT photo-polymerization, direct energy deposition, powder bed fusion, material jetting, binder jetting, and material extrusion. It is to be noted that not all these technologies can be used with food-based materials. Out of the above-mentioned technologies, the ones applicable in the food sector includes: extrusion, powder bed fusion, binder jetting, and material jetting (see Table 3).

**Material extrusion** process for 3d food printing involves layer by layer deposition of ingredients through a moving, often heated nozzle system. The technology was developed in the early 1990s by S. Crump, and was primarily used for creating 3d prototypes using plastic filaments (Crump, 1992). It was recently adapted to be compatible with food ingredients. Such an adapted setup includes one or more cylindrical extruders (canisters) in to which the

ingredients are loaded (Godoi, Prakash and Bhandari, 2016). Presence of multiple extruders offers the possibility to 3d print several food ingredients at the same time, resulting in more complex food designs. Another interesting possibility of material extrusion 3d food printing is in utilizing dual feed extruders for creating custom colours, by mixing accurate proportions of two food ingredients with different colours (Izdebska and Zolek-Tryznowska, 2016).

Extrusion 3d food printing can further be classified in to three categories depending on the associated binding mechanism, i.e., soft-material extrusion, melting extrusion, and hydrogel-forming extrusion (Godoi, Prakash and Bhandari, 2016). Soft-material extrusion technique is used to print ingredients that can form self-supporting layers. Such materials include cake frosting, processed cheese, dough, and meat paste (see Figure 9). The underlying binding mechanism is closely associated with the rheological properties, especially viscosity of the food raw materials. The material should be flowable enough to pass freely through the narrow nozzle, at the same time should retain the structure geometry after deposition. Additives that comply with the food safety standards are often used to achieve desired rheological characteristics.



*Figure 9: Soft material-extrusion 3d printing (Source: Natural Machines).*

In case of melting extrusion, print material is heated slightly over its melting temperature, often between 28 °C and 40 °C (Hao *et al.*, 2010; Godoi, Prakash and Bhandari, 2016). This is done to aid the binding mechanism that involves solidification of the melted material upon deposition. Melting extrusion process is widely used for creating customized 3d chocolate structures (see Figure 10) (Yang, Wu and Liu, 2001; Hao *et al.*, 2010). Binding mechanism of the third category of material extrusion 3d food printing, i.e., hydrogel-forming extrusion, is based on ionic or enzymic cross linking. Therefore, rheological characteristics of the food raw materials along with the gel forming mechanism play an important role in the process (Godoi, Prakash and Bhandari, 2016).



*Figure 10: Chocolate structure made using melting extrusion (Source: ChocEdge).*

Material extrusion 3d food printing is a comparatively cost-effective way of fabricating complex food structures. It is important to note that since material extrusion is one of the most widely used 3DP technology, the advancements of that area is comparatively higher. A lot of food ingredients naturally exists as pastes or puree, and it is relatively easy to convert many edible ingredients into extrusion compatible forms, making the technology quite reliable. The size of extrusion based 3d food printers are compact, making it suitable for home and restaurant use. The associated maintenance cost is also low. On the contrary, output quality of extrusion printing is often not very impressive. Long fabrication time, susceptibility to delamination, and presence of seam line between layers are some other disadvantages of this technology (Sun, Zhou, *et al.*, 2015).

**Powder bed fusion** is another popular system in 3d food printing, which is characterized by the application of a heat source to fuse together layers of powder. The process can be further classified in to Selective Hot Air Sintering and Melting (SHASAM) and Selective Laser Sintering (SLS) depending on the heat source utilized. An infrared laser setup acts as the heat source in case of SLS, while hot air is used to heat up the powder in case of SHASAM. Both the techniques involve a phase change as the evenly distributed food particles on the bed are melted and sintered together by the heat source moving in the x and y axis. The sintered layer is lowered, and the next layer of powdered food particles are distributed on the bed. This process continues until the final food product is formed. The excess powder on the bed will provide structural support during the sintering process. It is to be noted that both the powder bed fusion techniques requires an additional process step at the end for removing unfused food powder (Godoi, Prakash and Bhandari, 2016).

Powder bed technologies can be used for fabricating food-grade art objects and toffee shapes. The powders are mostly sugars or other low melting point substances that are rich in sugar, for example, Nesquik. SLS and SHASAM can print much complex designs in better

quality compared to material extrusion technologies. Powder bed technologies are comparatively faster, and do not require additional post-processing operations. On the other hand, the whole set-up is more expensive than that of material extrusion, and at the same time consumes more power. Most importantly, food grade materials that are compatible with powder bed technologies are very limited at the moment (Sun, Zhou, *et al.*, 2015).

Food structures printed using SLS and SHASAM are illustrated by Figure 11 and Figure 12 respectively.

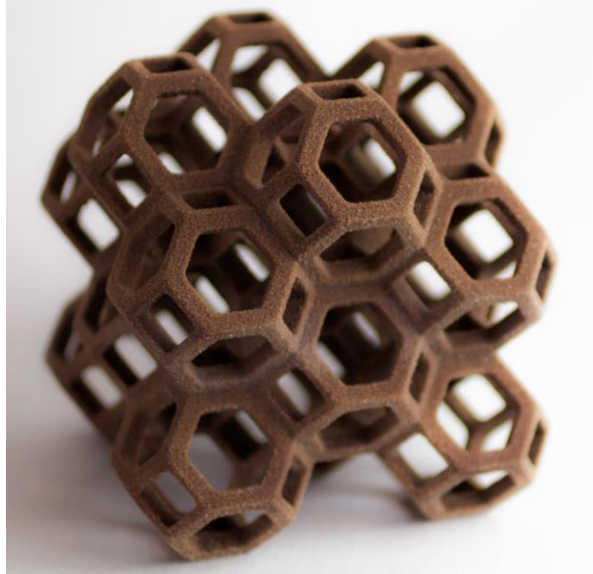


*Figure 11: Food objects created by TNO using SLS (Source: TNO).*



*Figure 12: Sugar structure made using SHASAM (Source: Evil Mad Scientist).*

**Binder jetting**, specifically liquid binding (LB), is another 3d printing technology that has been recently adapted for food fabrication. In this process, thin and uniform layers of powder are combined by a liquid binder that is dropped on demand by a movable print head. Like that of powder bed fusion methods, an additional de-powdering step is present in binder jetting. But unlike SLS and SHASAM, the final product of binder jetting undergoes a curing process. This finishing step also strengthens the layer connections. Powders compatible with this method include sugars, starch, corn flour and other food grade flavours. Liquid binding food fabrication can create complex food designs at a faster rate. It also has a full colour potential, and provides more material choices for printing. On the flip-side, the printing set-up itself is expensive at the moment, and the final outcome often suffers from a rough surface finish (Sun, Peng, Yan, *et al.*, 2015). Figure 13 illustrates an example of 3d chocolate structure that can be made using liquid binding technology.



*Figure 13: Chocolate structure made using LB technology (Source: 3D Systems).*

**Material jetting** is the final category of 3d printing that is compatible for food fabrication. The working principle of material jetting 3d printing is quite like that of traditional paper printing using inkjet printers. Both technologies utilize a drop-on-demand mechanism. In case of material jetting food printing, an edible food material is used instead of a printing ink. This process category can be further classified into bio-printing and inkjet printing. Inkjet printing utilizes low viscosity materials like pastes and purees, whereas bio-printing utilizes organic raw materials and cultured tissues. It is to be kept in mind that in addition to material jetting method, biological components can also be deposited using micro-extrusion and laser-assisted printing techniques (Godoi, Prakash and Bhandari, 2016). The biggest advantage of inkjet printing is its printing quality, making it suitable for producing customized cookies, biscuits, and cup-cakes. It can also take in ingredients in the form of batter or soft dough, which can then be turned into pizza bases and pancakes. Whereas, bio-printing has the ability in bringing food commodities based on cultured meat (artificial meat) to the mainstream. The print heads and platforms used in inject food printing are expensive, and the materials that are compatible with this technology are limited now.

Most food products, especially the healthier ones, are multi-component mixtures with complex rheology. However, most of the presently available 3d printing technologies cannot print multiple food materials simultaneously. With an exception for powder bed techniques, there exists a possibility to scale-up the existing printer designs to incorporate multiple print heads. Such a set-up will give the capability of controlling layer by layer material composition and distribution (Sun, Peng, Yan, *et al.*, 2015). This in-turn results in much complex food designs with personalized composition and flavours, improving consumer desirability. Researchers at Cornell University has already tested the material extrusion based Fab@Home 3d printer with multiple print heads. They have used edible materials including processed cheese, caramel, muffin mix, frosting, chocolate, hydrocolloid mixtures and cookie dough (Cohen *et al.*, 2009; Lipton *et al.*, 2010). The printing was done with the help of a secondary support material that was removed at process completion (Periard *et al.*, 2007). With the advancements in the field of food science, 3d food printers of the future are

expected to create complex multi-material food designs, utilizing a wider ingredient portfolio (Zoran and Coelho, 2011).

*Table 3: 3d food printing technologies (Godoi, Prakash and Bhandari, 2016).*

<b>Process category</b>	<b>Supply / Base materials</b>	<b>Technique</b>	<b>Compatible materials from literature</b>	<b>Working principle / Binding mechanism</b>
<b>Powder bed fusion</b>	Powder	SLS	Sugar, Nesquik	Laser heat source fuses the powder layers together / Sintering
	Powder	SHASAM	Sugar	Laser heat source fuses the powder layers together / Sintering & melting
<b>Binder jetting</b>	Powder	Liquid binding	Chocolate, flour, mixture of sugars, starch, mashed potato	Drop-on-demand liquid binder joins powder layers / Adherent potency or powder-binder chemistry
<b>Material jetting</b>	Liquid, paste	Bio-printing	Cultured meat tissues	Drop-on-demand of bio-based liquid or paste / Self-congregation of the tissues
	Liquid, paste	Ink Jet Printing	Cheese, jams, sugar gels, batter, chocolate, meat paste	Drop-on-demand of liquid or paste / Rheological properties of the material facilitates layering
<b>Material extrusion</b>	Liquid, paste	Soft-materials extrusion	Processed cheese, dough, meat puree, hydrogel, cake frosting, cheese, hummus	Deposition through extrusion / Rheological properties of the material facilitates layering
	Paste	Melting extrusion	Chocolate	Deposition through extrusion / Fusion of layers upon solidification (once the print cools down)
	Liquid, paste	Hydrogel forming Extrusion	Gelatine, gum	Deposition through extrusion / Fusion of layers through enzymic or Ionic interlinking



### 2.4.3 Significance of 3d food printing

3d food printing coupled with an effective business model offers a huge innovation potential. It is an eco-innovative and cost-effective technology that will help in creating mutually beneficial outcomes for all actors in the food value chain, including ingredient producers, processing brands, distributors, and consumers. Adapting 3d printing technology for food fabrication will also help in minimizing food wastage associated with traditional production processes, resulting in bio-economy with a sustainable food system. Tackling the challenge of food scarcity/ security is another obvious out-turn of 3d food printing. It allows the industry to shift focus from mass producing food-product varieties to innovating and producing enough ingredients to feed the growing population (Tran, 2016). Food raw materials that are pre-packed in cartridges usually have a longer shelf life than convenience food, fresh fruits, and vegetables. These food cartridges, customized with essential nutrients, can be sent to locations with limited food access (Lin, 2015). Additionally, localized food production utilizing 3d food printers will reduce the overall carbon footprint associated with the food supply chain, tackling the challenge of climate change.

The value of 3d food printing really depends on where it is used, and how. Under the current market conditions, its key business value is in differentiating companies from their competitors, and to bring them on par with the latest innovation trends. Also, early adopters get the advantage of having the research and innovation tailored to their own product. Barilla's collaboration with TNO (Van Bommel, 2014; Van Der Linden, 2015) and Hershey's collaboration with 3D systems (Molitch-Hou, 2015) highlights this argument. The R&D that has gone into creating the shaped pastas and chocolate structures is tried and tested with the recipes of Barilla and Hershey respectively. Their competitors will most likely have to reformulate their recipes to get most out of the technology. Most of the food companies discern that fact that 3d food printing cannot compete in price with regular food production technologies at present. Therefore, rather than replacing traditional manufacturing completely (Lin, 2015), 3d food printing could help businesses in capturing value from high-end niche applications. This also gives businesses the opportunity to innovate new business models and eliminate the outdated ones (Tran, 2016).

In Michelin-star restaurants, value for the experience factor is multiple times the value of ingredients. In other words, consumers pay for the overall eating experience, and not just for the meals. Premium food designs that complies with consumer preferences are a great value generator for such businesses. 3d food printers give Michelin-star chefs the design freedom to create innovative shapes, textures, and flavours (Van Der Linden, 2015), whereas building complex food structures by hand is rather difficult and time consuming. Digital platforms combined with 3d food printing enables food brands to connect better with the consumers and co-create with them. This in-turn translates to innovative food designs with higher market potential and desirability. It is also a good prototyping tool for chefs and researchers in the field of food processing (Sun, Peng, Yan, *et al.*, 2015).

3d food printing could aid SMEs in their branding and marketing activities. The novelty value of the technology attracts a lot of people. Magic Candy Factory for example has the printers in some of the flagship stores of Katjes, a candy (*Magic Candy Factory*, 2015). Hence 3d food printing could also be used to create attention and attract people to the store, where they may buy non-3d printed products or 3d printed ones. Additionally, alternate food ingredients like protein from algae, fava beans, beet leaves and insects can be turned into

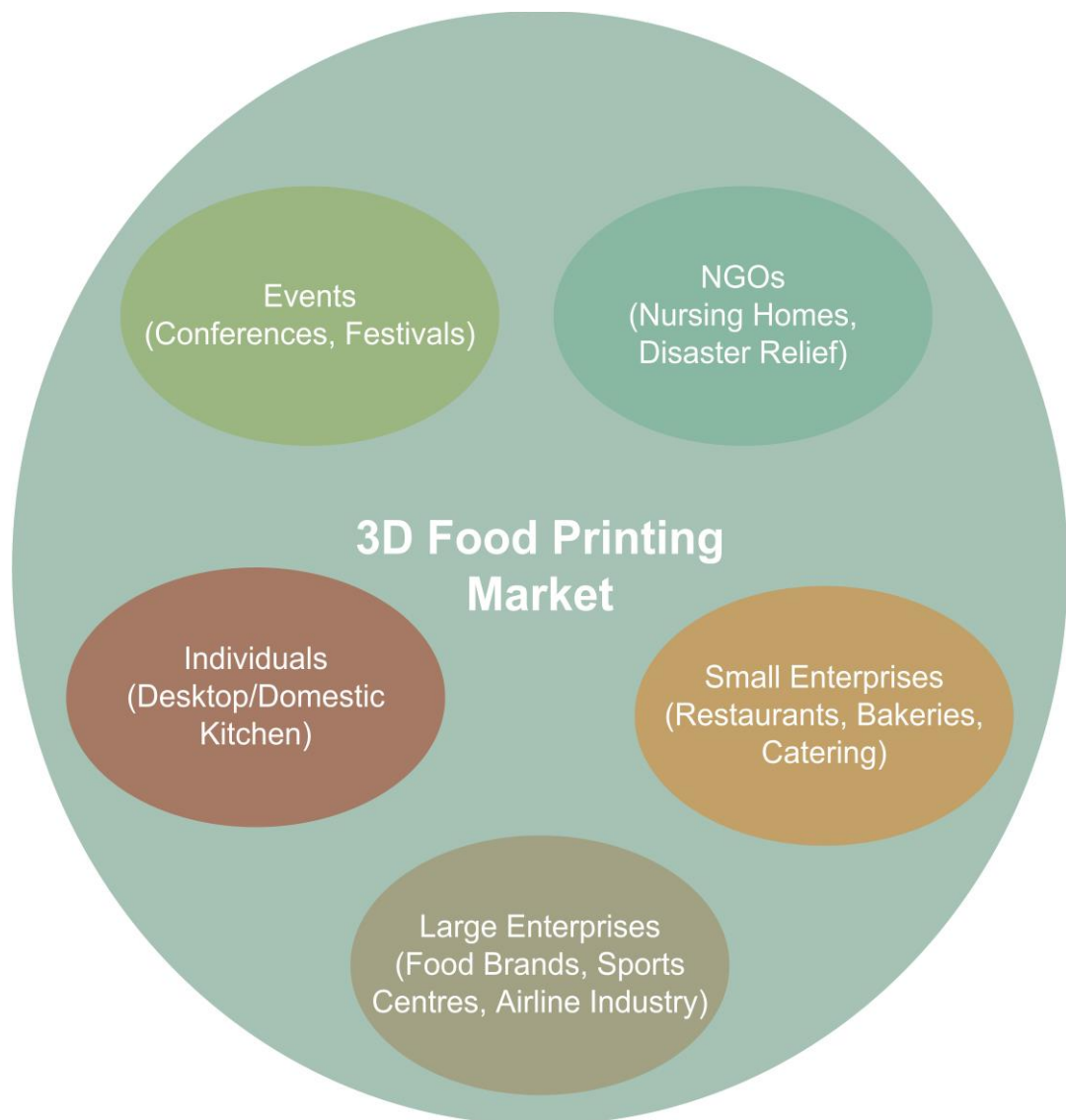
desirable food products using 3d food printers (Van Bommel, 2014). This creates a value for businesses targeting sustainability-conscious consumers. 3d food printing or AFM also opens-up interesting possibilities for consumers, in terms of food customization and personalized nutrition. 3d food printing is a very flexible production technique, which allows consumers to customize their meal based on their personal requirements, allergies, health issues and so on. Personalized nutrition is gaining popularity as more people are becoming aware of what a well-planned meal can do for health, fitness, and recovery (Van Bommel, 2014; Van Der Linden, 2015; Tran, 2016). Certain consumer segments like military personnel, and astronauts require nutritious food that lasts for extended periods of time. 3d food printing is found to be the perfect solution for this challenge (Hall, 2013; Tran, 2016). Personalized food raw materials can be stored and transported in ready-to-print cartridges/ capsules. These cartridges can then be plugged-in to remotely located 3d food printers to produce fresh, healthy, and personalized meals (Lin, 2015).

Lastly, AFM fosters consumer convenience, at the same time brings-in a social, interaction, and fun aspect to food preparation and consumption. Researchers (Wei and Cheok, 2012) argues that this interactive and playful aspect enhances the overall eating experience. A research team at University of Foggia suggested that 3d food printing could have a significant impact on child nutrition. Interesting food shapes possible with 3d food printers could encourage kids to consume fruits and vegetables that they otherwise wouldn't eat (David, 2017).

#### **2.4.4 Market segmentation**

The current competitive landscape of 3d food printing is dominated by players from Europe and North America. There has also been some significant developments in Asia, especially China, Taiwan, Japan, and Korea (Sullivan and Frost, 2015). It is interesting to note that almost all the microwaveable pancakes available in Dutch supermarkets are 3d printed. Spain is also spearheading the market with multiple players targeting households and restaurants. Most of the 3d food printing related research in USA are associated with 3D Systems and Culinary Institute of America (Persistence Market Research, 2016). 3d food printing is a relatively new technology innovation, with a dynamic scope of application. While the technology is being refined and new business models are being innovated, its market reach is predicted to increase in the coming years (Sullivan and Frost, 2015).

Based on the existing literature, and predictions made by marketing and future-foresight firms, the market segments for 3d food printing can be categorized in to five clusters (see Figure 14) (Van Bommel, 2014; Lin, 2015; Sullivan and Frost, 2015; Van Der Linden, 2015; Persistence Market Research, 2016). The first cluster includes large enterprises like food brands, sports/ fitness centres, government establishments, and airline companies. Second cluster includes small scale enterprises like restaurants, bakeries, and catering. In the first two market clusters, food fabrication can either be centralized or local, depending on the use-case. The third market segment is desktop/ domestic kitchen, where individuals locally produce personalized meals for their own consumption. The next cluster includes nursing homes and other NGOs like disaster relief organizations. Final market cluster is for events like conferences, which new 3d food printing businesses utilize as a marketing platform to show-case their innovation. The mode of food fabrication in the last two clusters can either be centralized or localized.



*Figure 14: Market segmentation for 3d food printing.*

## **2.5 Current 3d food printing ecosystem**

An ecosystem is a nexus of all individuals and enterprises, whose interactions are critical in creating, delivering, and capturing value within an economy. The current ecosystem for 3d food printing is comprised of nine key actors (see Figure 15), namely, research centres and universities, makers of 3d food printers, food ingredients producers, distributors, food brands and restaurants, software developers, online platforms, market places, and consumers. Depending on the nature of interaction between these identified actors, 3d food printing ecosystem can contain multiple value chains. It is to be noted that not all the actors of the ecosystem will play a role in individual value chains.



*Figure 15: 3d food printing ecosystem highlighting main actors.*

### **2.5.1 Existing 3d food printing value chains**

The two most prevalent value chains for 3d food printing has been identified and illustrated in this section (see Figure 16 and Figure 17). The first value chain (see Figure 16) is associated with the market clusters of small and large enterprises. In this value chain, 3d food printing hardware and software are sold to enterprises like food processing brands, restaurants, and bakeries. These food brands acquire raw materials required for 3d food printing from ingredients producers. Consumers select the food product, and orders it from the web store of food enterprise. Once the order is made, the product is 3d printed, packaged, and delivered to the consumer.

The second value chain (see Figure 17) is associated with the market segment of desktop/ domestic kitchen. In this value chain, consumer buys desktop 3d food printer from the manufacturer. Using the food raw materials purchased from local groceries or supermarkets, consumer prints food designs for their own consumption. They often use the digital service provided by the 3d food printing company to download food designs and recipes. Here the term consumer is used instead of prosumer, because the level of prosumption is minimal. Consumers can make some design customizations using an online platform, but cannot personalize the food product in terms of ingredients, textures, and nutritional content.

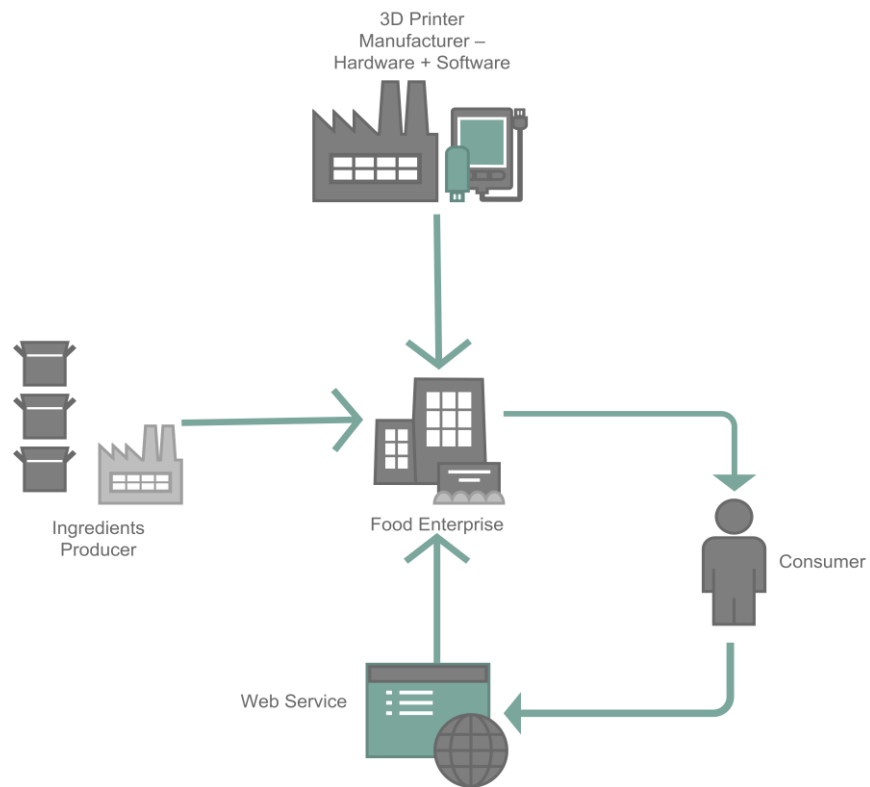


Figure 16: A food value chain with 3d food printing: Consumer buys 3d printed food.

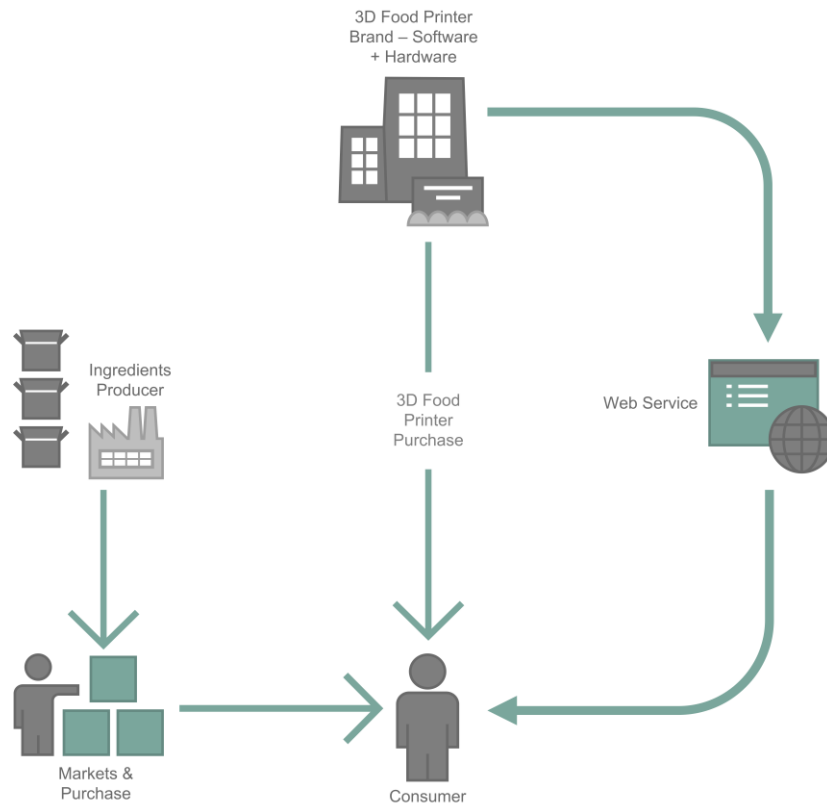


Figure 17: A food value chain with 3d food printing: Consumer buys 3d food printer.

## 2.5.2 Existing 3d food printers and research prototypes

The first patent related to 3d food printing was filed by Nanotek Instruments Inc. in 2001. While they defined a method for creating food products like customized cakes (Yang, Wu and Liu, 2001), no physical prototypes were made. The technology went through a hibernation until 2007, when researchers at Cornell University developed a soft-material extrusion based 3d food printer. They modified the Fab@Home Model 1 open source machine to incorporate two extrusion heads for printing materials like cake frosting and processed cheese (Periard *et al.*, 2007). The same machine was improved later for printing sugar cookies (Lipton *et al.*, 2010) using a natively printable dough composed of egg yolk, butter, and sugar. Another initial development in 3d food printing was the CandyFab 3d sugar printer made by Windell Oskay and Lenore Edman of Evil Mad Scientist Labs (CandyFab, 2006). The printer used SHASAM technology for printing coarse sugar granules (see Figure 12). MIT developed a machine concept called Chocolatier as part of the Cornucopia project in 2010 (Zoran and Coelho, 2011). As per the concept, the machine has cartridges that can mix the ingredients. Mixed ingredients are then transformed in to edible compounds before being converted in to aesthetically pleasing designs.

3d food printing scene in Europe started developing once TNO of Netherlands came up with the SLS based 3d food printer in 2010. It was able to print structures made from powders with added nutrients and flavours (Van Bommel, 2014). The very next year, ChocEdge commercialized the first chocolate printer named Choc Creator. Its updated version, Choc Creator 2.0 is currently available in the market (Choc Edge, 2011). It works on an FDM platform in which chocolate is melted and extruded through a nozzle system. Figure 10 shows a spiral chocolate structure made using Choc Creator 2.0. Keeping food system sustainability in mind, Susana Soares kickstarted a project called Insects AU Gratin. As part of the project, edible insects are powdered and mixed with flavours, firming agents, and other additives. These powders are then turned into aesthetic looking 3d food structures (Soares, 2011) using extrusion technology. The project succeeded in creating desirable looking food products using a sustainable alternate ingredient (see Figure 18).

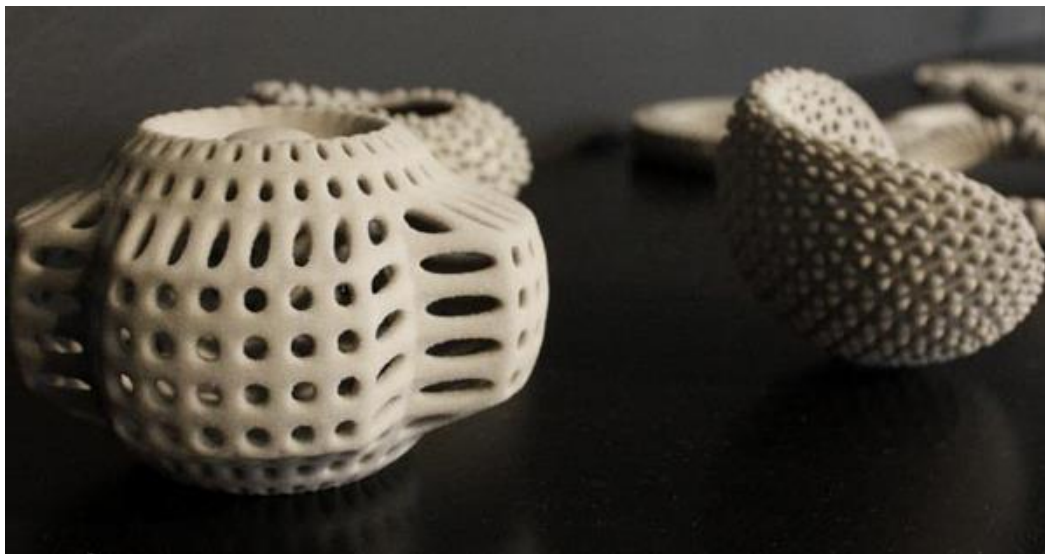


Figure 18: Food structures made of insect powder (Soares, 2011).

Systems & Materials Research Corporation (SMRC), a USA based start-up, introduced Chef3D pizza printer in collaboration with NASA. The company later changed its name to BeeHex. Along with NASA, they are currently investigating the feasibility of printing healthy and nutritious meals for astronauts on extended space trips (Hall, 2013; Alec, 2016). In the same year 3D Systems along with the culinary labs in USA introduced the ChefJet series of 3d food printers in market. The ChefJet Pro printers utilizes liquid binding technology for creating a wide variety of confectionary products like sweet and sour candies (Gold, 2014).

In 2013, two key developments happened in the European 3d printing scene. First is the 3d pasta printer concept developed by TNO in collaboration with Italian food company barilla (Van Der Linden, 2015). Barilla is still refining the technology and is aiming to target the printer towards both domestic kitchens and fine dining restaurants. Second is the arrival of Foodini 3d food printers developed by Natural Machines. The machine developed by the Barcelona based start-up can print a wide variety of dishes using natural ingredients. It has a touch screen interface that enables the user to choose recipes from a cloud platform, making it one of the very few 3d food printers that can be controlled using a smart device (Prisco, 2014). It uses soft-material extrusion process for 3d printing food structures, and comes with re-usable capsules. Foodini is still being refined and Natural Machines are planning to integrate a cooking system to it in the future (Natural Machines, 2013).

By 2014, a lot of new players have already entered the 3d food printing market. Patent applications in the field also have increased drastically by then (Sullivan and Frost, 2015). Dutch company byFlow introduced Focus 3d food printers, and German enterprise Print2Taste unveiled Bocusini printers for professionals. RIG from Barcelona also introduced their extrusion based machine in 2014. In USA, Hershey collaborated with 3D Systems to develop a chocolate 3d printer called ChocJet, which is based on melting extrusion 3d food printing technology. Some other notable players in the current 3d food printing ecosystem includes Katjes Magic Candy Factory (*Magic Candy Factory*, 2015) in UK, Nu food robot (NuFood, 2015) in UK, and XYZ Printing in Taiwan (Alec, 2015).

Nestle Institute of Health Sciences (NIHS) in Switzerland came up with an instant-nutrient food machine concept as part of a program called “Iron Man”. The program is aimed at tackling malnutrition, by measuring and controlling nutrients in individual meals (Begley, 2014). Another milestone in 3d food printing related research is the EU funded Performance project (Bardenstein *et al.*, 2014; Performance, 2015) that aimed at facilitating personalized nutrition in elderly people. It combined personalized 3d food printing with personalized packaging. The package concept for the 3d printed food includes an identification code, and a 3d printed pattern for controlling food temperature. Projects like performance and ironman are showing the true personalization potential that 3d food printers are having. An innovative digital platform combined with latest ICT will act as a catalyst in the mainstreaming of such 3d food printing concepts. Such a platform will allow prosumers to get most out of the 3d food printer. As both ICT and 3d food printing technology continues to advance, prosumption possibilities are also expanding.

Major 3d food printer designs and research projects identified as part of this thesis are listed in Table 4. It is also to be noted that fine dining restaurants have started incorporating 3d printed food in their menu. Table 5 includes the list of restaurants that are already 3d printing either full meal or at least some part of the meal. The table also includes the name of 3d food printers being used by these restaurants, and the dishes they make using it.

Table 4: 3d food printer designs and research projects.

Printer Name	Developer	Location	Est.	Description
Fab@Home Model 1	Cornell University	USA	2007	Open source design 3d printer. Twin head extrusion using hydrocolloids, batters, and protein pastes
CandyFab 3D Sugar Printer	CandyFab Project, Evil Mad Scientist Labs	USA	2008	Controlled fusion (SHASAM) using coarse sugar granules
Phillips 'Food Printer'	Design Probes, Phillips	Netherlands	2009	Concept design: Customised food printing using pastes loaded in cartridges
Chocolatier	Cornucopia, MIT	USA	2010	Concept design: Melting extrusion using chocolate solids and pumpable fillings
TNO Laser-Fusion Printer	TNO	Netherlands	2010	Selective Laser Sintering using Sugars and Nesquik
Choc Creator	Choc Edge Ltd., University of Exeter	UK, China	2011	Melting extrusion based chocolate printing
Insects Au Gratin	London South Bank University	UK	2011	Extrusion printing using insect powders and firming agents
Chef3D	BeeHex	USA	2013	Extrusion based printer born from a NASA project
ChefJet Pro	3d Systems, Culinary Labs	USA	2013	LB based 3d food printer for professionals
Pasta Printer	TNO, Barilla	Italy	2013	Soft material extrusion using pasta dough
Foodini	Natural Machines	Spain	2013	Extrusion based 3d food printer
Focus	byFlow	Netherlands	2014	Extrusion based 3d food printer
Bocusini	Print2Taste GmbH	Germany	2014	Marzipan and chocolate printer for professionals
Food Form 3D	Robots in Gastronomy (RIG)	Spain	2014	Soft material extrusion based printer
ChocJet	Hershey, 3D Systems	USA	2014	Melting extrusion based chocolate printer
Nestle Food Replicator	NIHS Iron Man Project, Nestle	Switzerland	2014	Concept design: 3d food printing for fighting deficiencies
Magic Candy factory	Katjes	UK	2015	3d food customization platform and marketplace for gummy candies
Nufood food robot	Nufood	UK	2016	Building 3d structures from liquid ingredients



*Table 5: Restaurants/ food producers utilizing 3d food printing.*

<b>Name</b>	<b>Location</b>	<b>Food Printer</b>	<b>Description</b>
Food Ink	London, UK	Foodini	Entire dining experience utilizing 3d printers
Millesse Restaurant	Santa Monica, USA	ChefJet Pro	Crafting crouton in onion soup
La Enoteca at Hotel Arts	Barcelona, Spain	Foodini	Seafood coral designs
La Boscana	Barcelona, Spain	Focus	Gourmet eatery

### 3 Research design

This chapter deals with the process and methodologies used to answer the identified research questions. It describes the way in which empirical data was gathered, analysed, and interpreted. This chapter is divided into three sections. First section describes the process followed, i.e., the double diamond model. Second section introduces the paradigm of mixed methods research that was used for collecting and analysing data. A detailed description about the qualitative research conducted in the form of expert interviews, and the quantitative research carried out in the form of expert survey is provided in this section. The framework used for the stakeholder workshop is also explained. In addition to answering how the approach/method/tool was used, each section also describes why it was used.

#### 3.1 The process: Double diamond process model

This master's thesis work followed a modified version of double-diamond model that was developed by the Design Council, UK (Design Council, 2005). The human-centric model was developed in 2005 to serve as a general template to any design and innovation process. Double diamond model is a combination of four interconnected phases, namely discover, define, develop, and deliver (see Figure 19). Each phase is associated with a distinct way of thinking. The first phase should be approached with a divergent mode of thinking, and is all about gathering fresh insights from multiple perspectives. Additionally, various methods and tools are to be reviewed at the beginning of this stage, and the most desirable ones chosen. In the define phase, all the insights gathered are to be analysed and grouped into clusters using tools like affinity diagrams. Hence a convergent mode of thinking is required. Here it is also important to identify the most relevant data sets for further developmental activities. Originally, the goal of this phase is to frame the given challenge into a creative brief. The third phase of the process should be approached with a divergent mode of thinking. Here multiple concepts are created and tested with an aim to answer the identified design brief. In the deliver phase, final concepts are selected and refined further before handing it over (Design Council, 2007).

Double diamond process model is made to be suitable for use in a variety of disciplines. It is meant to be modified to suit the project in hand. Also, each phase of this process model could be tweaked independently depending on the nature of project and the ways of working (Nessler, 2016). This flexibility is its biggest advantage. The topic of this master's thesis is a combination of 3d printing, food science, and ICT enabled prosumption. It is truly interdisciplinary in nature, and naturally demands a dynamic and multi-perspective approach like double diamond process model. Here, the original process model has been modified by keeping the thesis scope in mind (see Figure 19). In the first phase, the topic of prosumer driven 3d food printing was explored from different perspectives. Here multi-disciplinary literature reviews and expert interviews were carried out based on the identified themes, namely food value chain, prosumption, and 3d food printing. Importance was given to gathering fresh data from multiple sources. In the second phase, the collected data were analysed using affinity diagrams. Data were grouped into different clusters, and its relevance studied with respect to the research scope. The most relevant clusters were the ones that answered the research questions, i.e., the change drivers, key challenges, and uncertainties in prosumer driven 3d food printing, characteristics of the prosumer platform, key customization parameters, and potential prosumer archetypes. To quantify these data clusters, an expert survey was carried out. Survey analysis was also completed in the define phase itself. In the third

phase, use-cases were developed for the potential prosumer archetypes, and three of them were selected for further development. Flow diagrams were used to express the selected use-cases. A stakeholder workshop was conducted in the final phase of the thesis with an aim to further refine the use-cases, and to identify their developmental potential.

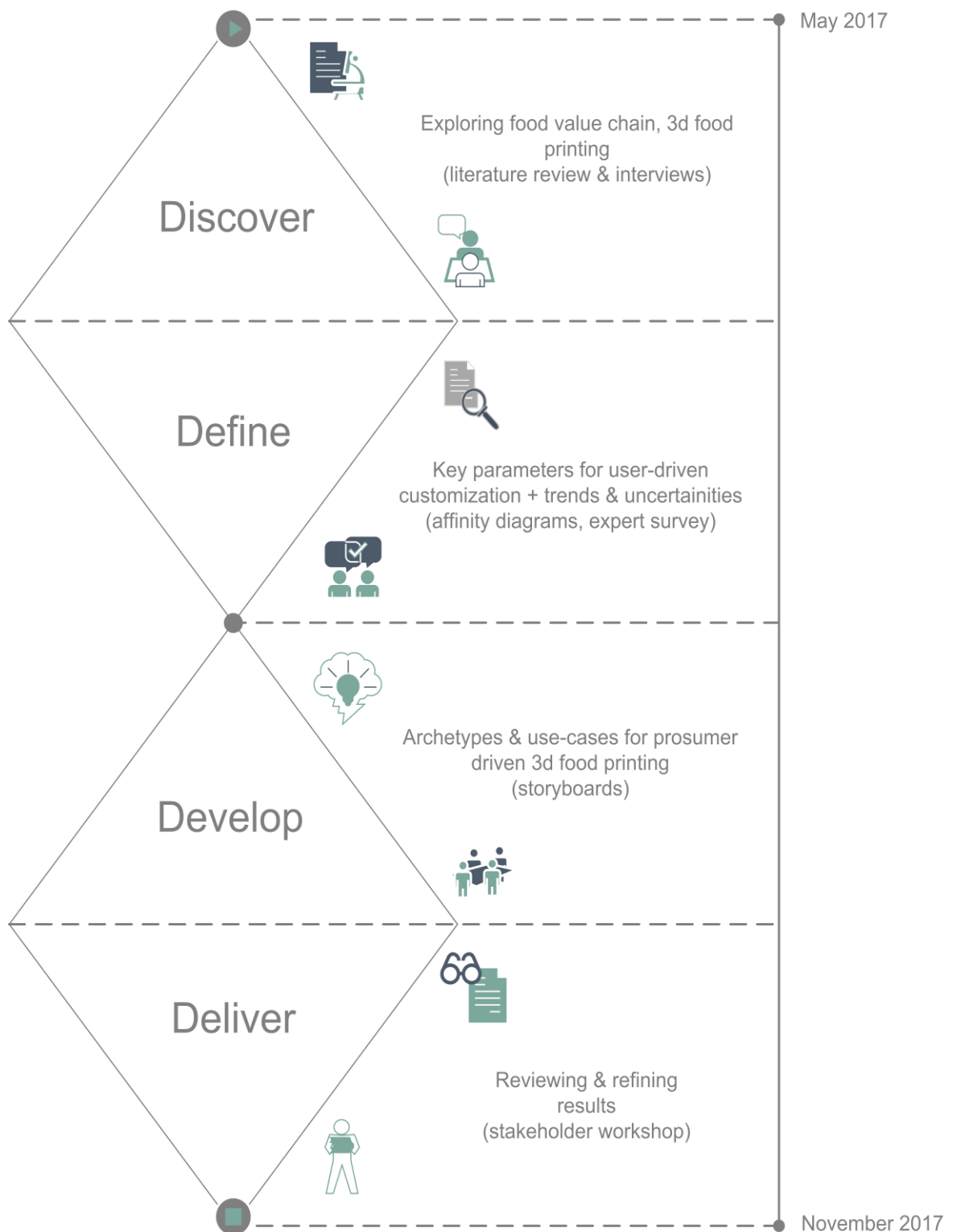
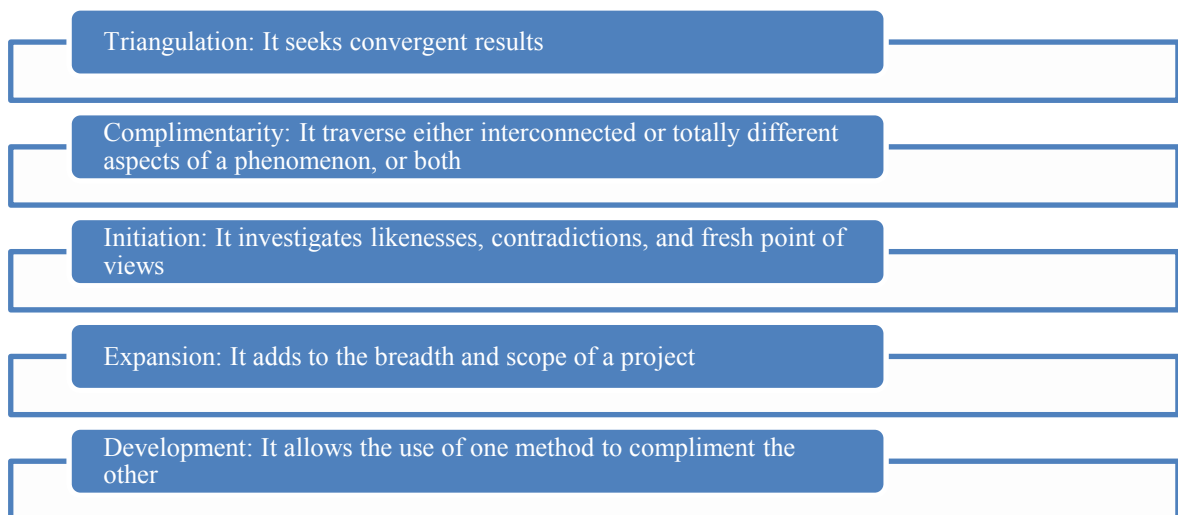


Figure 19: Research process: The double-diamond process model.

### 3.2 Data collection paradigm: Mixed methods research

Mixed Methods Research (MMR) methodology has been utilized in this master's thesis to collect, analyse, and interpret empirical data. It is a more specific version of the multimethodology approach that was introduced to the scientific world during early eighties. Multimethodology refers to the use of multiple research methods as part of a study or a group of related studies. The book 'Multimethod Research: A Synthesis of Styles' (Brewer and Hunter, 1989) written by John Brewer and Albert Hunter in 1989 gave mainstream attention to this approach. Mixed methods research is a subset of multimethodology, which involves systematic integration of qualitative and quantitative data as part of a study or a group of related studies (Creswell, Sobczak and Lee, 2003). This methodology became popular in social science disciplines during the nineties, and was later adopted by natural science disciplines (Wisdom and Creswell, 2013).

Mixed methods research is a pragmatic approach that facilitates a wider world view of the research subject, at the same time seeking convergent results (Greene, Caracelli and Graham, 1989). It is based on the idea that research questions should determine the methods to be used. Different phases of a research project are often characterized by different set of requirements, and hence demands different paradigms. MMR is found to be highly feasible and desirable in such projects. It offers enough freedom for researchers to employ different methods during different phases, depending on the nature of job in hand. Methods can be used in such a way that one compliments the other. For example, data from in-depth interviews could be used for building and structuring a survey. It is especially valuable when one phase of research is built over another one (Creswell, Sobczak and Lee, 2003). Here it allows for maximizing strengths and minimizing limitations of individual methods used. Figure 20 summarizes the characteristics that are identified for this research methodology (Greene, Caracelli and Graham, 1989).



*Figure 20: Key characteristics of MMR (Greene, Caracelli and Graham, 1989).*

As mentioned earlier, MMR is an amalgamation of quantitative and qualitative methods. Qualitative research tools like interviews and focus groups are subjective and tries to view a problem from perspectives of one experiencing it. It is an inductive process that often results in theory formulation. It is text based and can either be structured or unstructured. This

method is most suitable for gathering in-depth insights from fewer cases. Quantitative methods like surveys on the other hand are objective, and relies on a deductive process to test pre-defined hypotheses that makes up theory. They have a fixed response system and are often number based. They are comparatively less in-depth, but can be used with a larger number of cases. One main characteristic of quantitative research is the associated statistical analysis, which is absent in qualitative methods. Also, quantitative methods are more generalizable compared to qualitative methods. While the reliability of qualitative methods is dependent on the skill of researcher, quantitative methods depends a lot on the platform (usually an online digital platform) used. Qualitative methods often have a smooth and easy planning stage, but a complicated analysis stage. This is entirely the opposite in case of quantitative methods (USDE, 2014). Table 6 highlights the differences between these two methods.

Table 6: Comparison of qualitative and quantitative methods (USDE, 2014).

<b>Qualitative Research</b>	<b>Quantitative Research</b>
Example: Interviews	Example: Survey
Inductive process which often leads to theory formulation	Deductive process that tests pre-constructed concepts/ hypotheses that constitute a theory
More subjective	More objective
Text based	Number based
Gives in-depth information from a small sample size of sources	Gives less in-depth information from a large sample size of sources
Un-structured / semi-structured	Fixed response options
Involves no statistical analysis	Involves statistical analysis
Research reliability and validity depends on the vigour & skill of researcher	Research reliability and validity depends a lot on the platform utilized
Analysis is time-consuming while planning is comparatively easy	Planning is time-consuming while analysis is comparatively easy
Less generalizable	More generalizable

It is clear from the above table that both qualitative and quantitative methods have its own advantages and disadvantages. Using MMR approach helps exploiting the best aspects of each method, minimizing individual disadvantages. It facilitates better presentation in case of huge assortment of divergent views, and helps in drawing a stronger inference. Since prosumer 3d food printing is a relatively new research topic with an interdisciplinary nature, it was decided to use an inductive approach in the first phase, and a deductive approach in the second phase. The selection in-turn allowed the researcher to explore the topic from a wide range of perspectives, but still achieve generalizable results.

### 3.2.1 Mixing the data

Four different research models are possible within MMR depending on whether qualitative and quantitative studies are carried out concurrently or sequentially (Curry *et al.*, 2013). These four models are illustrated in Figure 21. The mixing of data is completely dependent on the research model being used. First model is termed as convergent parallel design. Here both quantitative and qualitative data are gathered and analysed at the same time. The two results are then mixed together and the merger is interpreted. The second model is called explanatory sequential design. Here quantitative analysis is carried out first, and its results are used in the qualitative study. Finally, qualitative data is analysed, and results are interpreted. In other words, the result of the qualitative study is used to explain the quantitative research outcome. The third model is called exploratory sequential design. Here qualitative data is collected and analysed first. The result of this analysis is used to design the quantitative study. Finally, the quantitative data is collected, analysed, and interpreted. The last model is termed as embedded design. It involves either the collection of qualitative data during a quantitative study, or the collection of quantitative data during a qualitative study.

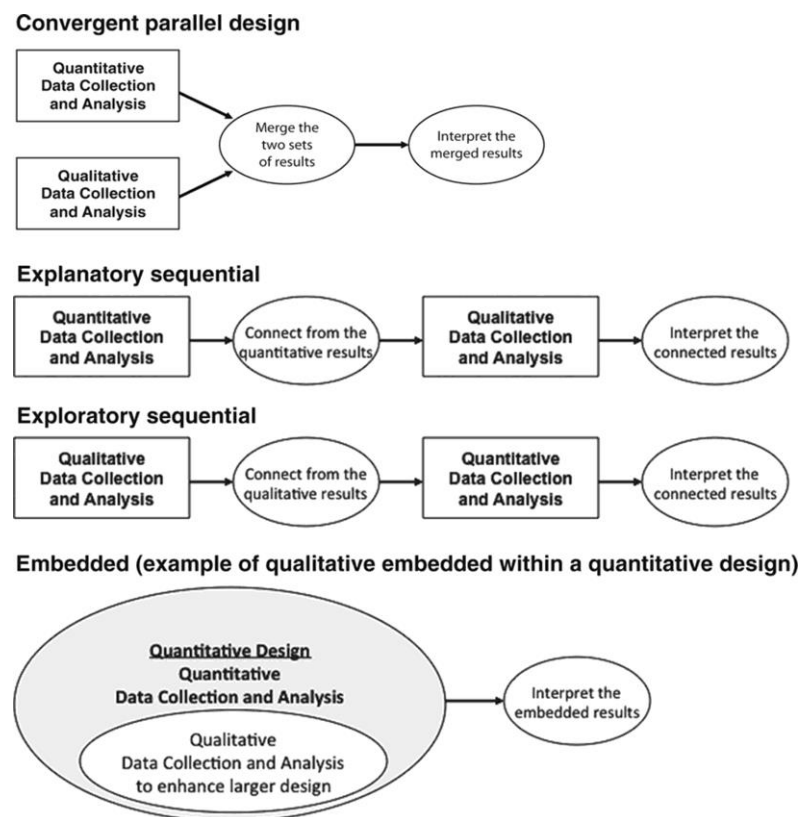


Figure 21: Four ways of mixing data in MMR (Curry *et al.*, 2013).

The research questions of the master's thesis demanded an exploratory approach, as described in the process model. There wasn't sufficient information at the beginning of the thesis process to conduct a quantitative study. Concepts/ hypotheses had to be constructed first by gathering in-depth information related to the topic. Therefore, convergent parallel design model and explanatory sequential model weren't considered. Embedding quantitative data collection within the qualitative study was one option, but the number of interviews

planned was not large enough for an effective quantitative study. Also, the qualitative components would have overshadowed the quantitative components. The above-mentioned arguments were critical while selecting exploratory sequential design as the research model.

### **3.2.2 Qualitative research: Semi-structured interviews with experts**

First step of selected MMR model, i.e., exploratory sequential design model, was to carry out a qualitative study. It is to be noted that this stage of the master's thesis was preceded by an extensive literature review process, where the state of the art of 3d food printing, food value chains, and prosumption were understood. The knowledge gathered from the literature review process was utilized in planning the qualitative study. The main intent of the study was to gain a broad perspective on the drivers and parameters for user driven customization in 3d food printing, the key trends as well as the uncertainties related to 3d food printing, and food production ecosystem in general. Semi-structured interview was selected as the method to gather qualitative data.

Semi-structured interview is a qualitative data gathering method in which a researcher interviews respondent with the help of a pre-determined, but informal set of questions. Unlike un-structured interviews, researchers can always maintain a good control over the interview with the help of the pre-determined topic areas and questions. This also means that they will be more confident while carrying out the interview (Cohen and Crabtree, 2006). A structured interview on the other hand gives the researchers total control over the interview, but takes away the freedom of respondents to make little deviations during the process. A semi-structured interview therefore strikes a fine balance between an unstructured interview and a structured interview, offering sufficient flexibility to both researcher and respondent. This flexibility aspect was critical while choosing the qualitative study method.

#### **Preliminary planning**

After finalizing the topic and scope of the interview, four questions were pondered upon. What should be the sample size (n) for the study? How should the interview be structured? Who all should be the interviewees? How should the data be recorded, stored, and analysed? Instead of having a pre-defined sample size, it was decided to prolong the interview process until fresh insights cease to uncover. Before finalizing the respondents, a general framework for the semi-structured interview process was made (see Appendix 1).

#### **Interview framework**

The interview framework consisted of questions grouped under five sections or themes, namely warmup and introduction, 3d food printing in general, future of food, ICT and rise of prosumers, and wrap-up. Time for each interview was set between 30 minutes and 45 minutes. The questions were determined keeping this time interval in mind. It was decided to start the warm-up and introduction round by briefly introducing researcher and the research, and then asking the respondents to introduce themselves with their education and work background. There was also a warm-up question for respondents, asking them their general opinion about 3d food printing. Second section had questions related to the value of 3d food printing to consumers and businesses; challenges regarding its feasibility, viability, and desirability; uncertainties and potential developmental areas. Third section included questions about trends and uncertainties in the food system, future food ingredients, and other developments in the food system that could compliment 3d food printing. Forth section

was all about ICT innovations, prosumption, and how they could add value to 3d food printing. There were also questions aimed at collecting insights about the characteristics and customization parameters for a prosumer driven 3d food printing platform. Final section had the wrap-up question asking respondents to envision 3d food printing in 2025. The framework (template) was tested and refined multiple times before the actual interviews.

### **Interviewee pool**

The research was carried out on a global scale, with an interviewee pool consisting of members from within the identified research themes, i.e., food value chain, prosumption, and 3d food printing. Research organizations, academia, future foresight consultancy, food producers, food processing brands, food distributors, 3d food printing businesses, software providers, hardware providers and service providers were part of the interviewee pool. Such a diverse pool was required because of the interdisciplinary nature of the topic. The selected interviewees had a wide range of expertise including industrial engineering, mechanical engineering, 3d printing, food science, material science, computer science, marketing, consumer research, innovation management, businesses strategy, prosumption, future food, and sustainability. Most of them were closely associated with 3d food printing, either through research projects or through their business. A small portion of the interview pool didn't have any association with 3d food printing. On the other hand, they were experts in their own fields, who could answer the pre-made questions. This was done to gain a fresh, unbiased perspective of the topic.

Once the contact details were acquired, personal e-mail invitations were sent to all the potential interviewees. They were briefed about the research project, and the nature of interview questions at this point of time. The interview framework was then customized for each interview, taking the background and expertise of the interviewee in to consideration. Finally, face to face interviews were conducted for participants within Finland, and Skype was used as the interview platform for participants outside Finland. For the first three interviews, the participants were requested to give feedback on the questions asked. Their feedback was used to further refine the interview framework for later interviews.

### **Overview of outcome**

15 interviews were conducted in total from 4 different countries. The participants came from a diverse background, and had a variety of expertise (see Table 7). This really helped in gathering fresh data related to the research topic from multiple perspectives. All the interviews went as smooth as it was planned, and often resulted in interesting conversations about the topic in hand. It is interesting to note that one interview went on to become a two-hour open conversation about the topic, even though the questions were planned beforehand. It in turn helped in gathering some constructive criticism about the technologies that were discussed as part of the research topic. Overall the qualitative data collection was a big success that resulted in a huge amount of interesting insights and information. Figure 22 illustrates the summary of qualitative study in one picture.



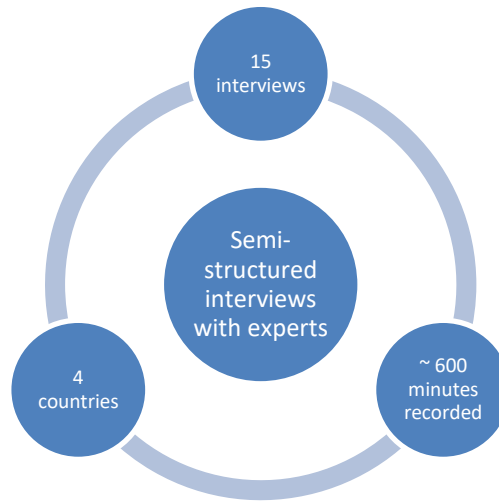


Figure 22: Overview of semi-structured interviews conducted.

Table 7: Details about the semi-structured interviews.

Organization and Role	Country of Location	Area of Expertise	Time taken
VTT, Senior Scientist	Finland	Food Science	30 minutes
VTT, Senior Scientist	Finland	Marketing	45 minutes
Natural Machines, CEO	Spain	Business Strategy	25 minutes
Natural Machines, Engineer	Spain	Engineering and Technology	30 minutes
TNO, Senior Consultant	Netherlands	Food Science	60 minutes
University of Nottingham, Researcher	UK	Food Science	40 minutes
byFlow, Engineer	Netherlands	Materials Science	45 minutes
3DTech Oy, Founder, Co-owner	Finland	Engineering and Technology	30 minutes
Senson, Innovation Manager	Finland	Business Innovation Management	30 minutes
DeskArtes Oy, Managing Director	Finland	Computer Science and Technology	25 minutes
Aalto University, Professor	Finland	3D Printing	30 minutes
Fazer Bakeries*, Head of Innovation, Director	Finland	Food Processing	45 minutes
VTT, Senior Scientist	Finland	Prosumption, Industrial Engineering	2 hour open discussion
Junior Consultant, Demos Effect	Finland	Future Food, Strategy & Sustainability	45 minutes
Selecta Oy AB*, Business Manager – Public Vending	Finland	Business Management	45 minutes

\*Visited the company facility in addition to the interview.

## Analysing data: Affinity diagrams

Experts have identified tape-recording as one of the best practice for registering the qualitative data (Cohen and Crabtree, 2006) during a semi-structured interview. It is particularly important because semi-structured interviews naturally allow the participants to deviate from the pre-determined framework. Presence of open ended questions make taking notes challenging during the interview process. To ensure that no data is lost during the process, all the interviews were recorded after taking permission from the interviewees. The recorded interviews were later transcribed in to text format for facilitating easy analysis.

Since the interviews generated a huge pile of relevant data, selecting the right tool for analysis was critical. Affinity diagram (Tague, 2004) is one tool that helps in organizing huge amount of data in the form of ideas and opinions based on their natural relationships. Here, the categories shouldn't be created beforehand and the data shouldn't be placed in any particular order. They are also a great means to visualize the gathered data. Affinity diagrams are most commonly used in group brainstorming sessions during new product development process. While it is common nowadays to use digital affinity diagrams (Widjaja and Takahashi, 2016), a paper based analysis was conducted during this thesis for the sake of simplicity. Data from the transcribed interviews were clustered in to six groups based on their affinity, namely change drivers, challenges and constraints, uncertainties, potential customization parameters, potential characteristics of a prosumer platform for 3d food printing, and potential application areas and archetypes for prosumer driven 3d food printing. Post-its, sketch pens, and chart papers were utilized in this process (see Figure 23). Clusters created using affinity diagrams are illustrated in section 4.1 of this master's thesis.



Figure 23: Affinity diagrams being made with the help of post-its.

### 3.2.3 Quantitative research: Online survey for experts

A quantitative study was conducted to make the qualitative research results more generalizable. The results of qualitative analysis were used as an input for the quantitative study by following the exploratory sequential design model of MMR. The main intent of the study was to quantify and further define the characteristics and parameters of a prosumer driven 3d food printing platform, and to evaluate the potential of the identified use-cases for it. Online survey was selected as the method to gather quantitative data.

Online survey (Andrews *et al.*, 2003) is a systematic process of gathering quantitative data from a pre-determined target audience. Here, the target audience (participants) are invited to answer a questionnaire over the internet. It is a comparatively easy research method to plan, and requires no or minimal monetary resources. The biggest advantage of online survey is the design flexibility it offers to the researcher. Present-day online platforms facilitate easy design of even some complex survey types. Also, the whole data handling process in case of an online survey is automated. The responses are stored in an online platform unlike a paper survey, hence minimizing handling related errors. It also offers a lot of convenience to the participants, as they are free to fill the survey in their own pace and time preference (Sincero, 2012).

### **Preliminary planning**

The survey scope was defined with regards to the number of questions and the time to answer. It was decided that the survey will consist of only closed-ended multiple choice questions. Researchers have found that the optimal length of an online survey should be 20 minutes, whether it is targeted to experts or not (Henning, 2013). Hence it was decided to design the questionnaire in such a way that answering won't take more than 20 minutes. The target audience for the survey was kept the same as that of the semi-structured interviews. On the other hand, the sample size was planned to be much bigger than that of the qualitative study. Next big step was the selection of the online survey platform. While a lot of free options are available currently, a professional survey tool called Webropol ([www.webropol-surveys.com](http://www.webropol-surveys.com)) was selected. The tool was freely available for the Aalto University students, and included an Aalto university survey template. The Aalto University template was chosen to make the survey as professional as possible.

### **Survey framework**

Soon after the qualitative data was analysed and clustered, a survey framework was planned. Here the main objective was to avoid ambiguities and maintain a clear and logical structure throughout. The survey framework had 11 multiple choice questions with 57 answer fields. The approximate completion time was set between 10 minutes and 15 minutes. Questions were structured in to five sections, namely taxonomy and background information, 3d food printing in general, prosumer platform for 3d food printing, use-cases for prosumer driven 3d food printing, and contact form with a thank you note. Each section of the survey was made to fit in its own page, so that the participants had to complete a section to see the questions of the next section. Before the first section, a brief introduction of the research project along with its context was given. A small description of the scope and aim of the questionnaire was also included. Except for the taxonomy section, all the questions were of a matrix form with a 7-point scale. In the 7-point scale, 1 denoted strong disagreement, 7 denoted strong agreement, and 4 denoted the in-between option. There was also an 'I don't know' option. Hypotheses from qualitative analysis formed the rows of the matrix, whereas the 7-point answer scale formed the columns. Once the questionnaire was logically structured, it was sent to 3 researchers for gathering detailed feedback. Questions were further refined based on the feedback, and framework was finalized. The survey framework is appended with this master's thesis for further reference (Appendix 2).

## Pool of respondents

Like the qualitative study, the survey was also targeted to experts within the identified research themes, i.e., 3d food printing, food value chain, and prosumption. A contact list of 85 experts was created during the planning phase. The list included authors of research papers studied during the literature review process, participants of the qualitative study, and 3d food printing businesses around the world. Since most of the contacts in the list were gathered from research papers, number of industrial experts in the pool were comparatively less. Once the survey framework was finalized, it was sent to all 85 experts by e-mail along with a personal invitation letter. The survey was active for 1 month, and 4 reminders were sent to the pool of respondents during this time. Once the responses were received, the survey data were exported to Microsoft Excel for analysis.

## Overview of outcome

The survey received an overwhelming response. The personally addressed e-mail invitations, and weekly reminders have played an important role in this positive response rate. 50 experts from 13 countries around the world have answered it (N = 50). Out of all the respondents, 31 are based in Finland (see Figure 24). While the number of respondents from outside Finland is comparatively less, the survey still managed to bring-in a global perspective to the quantitative study.

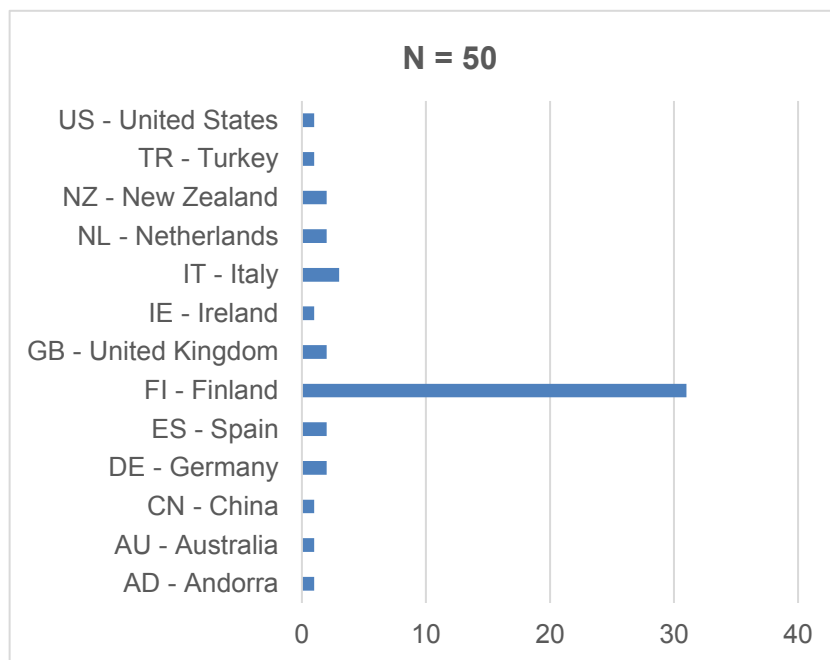


Figure 24: Location of survey respondents.

Figure 25 illustrates the primary field of organization of the survey respondents. Researchers made the biggest contribution to the study. 36 out of fifty participants are doing research work in either technical research organizations or academia. But it should also be noted that the study received contributions from almost every area of the food value chain, including 3d food printing companies, ingredient producers, food processing brands, food distributors, restaurants/bakery, and service/technology providers. Figure 26 illustrates the wide range of expertise that the survey respondents have. 50% of the respondents have an expertise in 3d

printing and around 25% have an expertise in 3d food printing. A significant number of participants have expertise in science disciplines including engineering, food science, material science, and computer science. Business related expertise of the respondents includes business strategy, marketing, innovation management, and industrial management. It is a very positive aspect that the respondents also possessed expertise in future of food, sustainability, prosumption, consumer research, food psychology, food certifications, telecommunication, IoT, design, and information security, especially considering the nature of research questions identified.

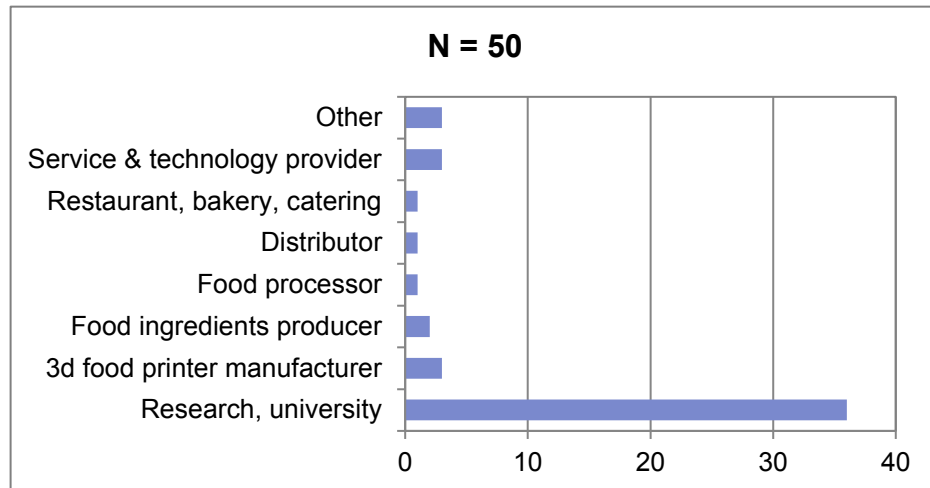


Figure 25: Primary field of organization of survey respondents.

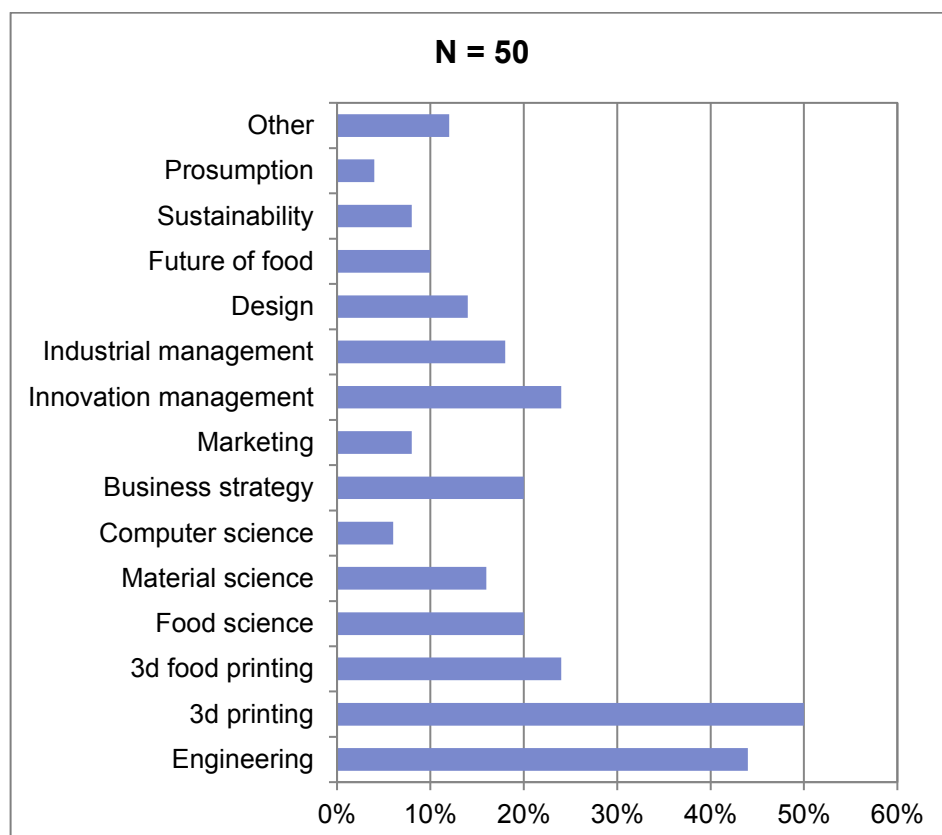


Figure 26: Field of expertise of survey respondents.

### 3.2.4 Challenges in mixed methods research

While MMR offers a lot of advantages over traditional methods, there are some challenges and limitations associated with it. Mixed methods studies are comparatively time-consuming and requires very careful planning. Three critical elements that needs to be considered during the planning stage are, qualitative and quantitative study sample; timing of the studies; and the mode of mixing data. These three steps are very much dependent on the chosen MMR model. Also, the amount of resources and labour required for MMR are much higher than that of a single method study (Wisdom and Creswell, 2013).

### 3.2.5 Stakeholder workshop

As mentioned in the preface, this master's thesis is a part of jointly-funded Tekes (Finnish Funding Agency for Innovation) project - 3D Surprise (Multi-layer food textures by advanced manufacturing technologies), in collaboration with VTT Technical Research Centre of Finland, Aalto University, and Finnish industry partners. Therefore, the results of this thesis are relevant to the 3D Surprise project stakeholders. A stakeholder workshop was conducted with an aim to further define the selected use-cases.

After the quantitative studies, 3 use-cases were selected based on its feasibility, business potential, and relevance to 3D Surprise project. These use-cases were further developed by adding prosumer-workflow models to it. These workflow models acted as storyboards, giving a narrative of the use-case. It is especially important for services which involves direct end user engagement. As part of the workshop planning, a doodle poll was conducted to identify the most suitable time. Length of the workshop was fixed at 2 hours. Once the date, time and number of participants were finalized using the doodle poll, a place was selected. As a next step, workshop frameworks were created for each of the 3 use-cases. The framework (see Appendix 3) for each use-case consisted of 3 steps as illustrated in Figure 27, i.e., understanding how the service works, how is it going to be implemented, and what impact will it create on the value chain.



Figure 27: Stakeholder workshop steps.

Majority of the people who signed-up for the workshop were researchers, either from Aalto University or from VTT Technical Research Centre of Finland. There were also a few representatives from the Finnish industry. The participants were teamed-up into 3 multi-disciplinary groups beforehand. During the 2-hour workshop, each of the team worked on all 3 use-cases. Since they only had 20 minutes to work on each case, workshop facilitation was

very important. The teams were continuously monitored by the facilitator (researcher), helping them whenever it was necessary. In the last 10 minutes of the workshop, each team presented what they have been discussing, and gave a comparison of the 3 use-cases.

Figure 28 shows 3 teams working on the use-cases during the workshop.









*Figure 28: Stakeholder workshop conducted as part of the thesis.*

## 4 Research findings

This chapter of the thesis presents all the main results from the research work carried out. It is divided into 3 sections, namely findings from qualitative research, findings from quantitative research, and further developments. This order is followed because of the nature of research methodology used. This chapter includes the answers to all the research questions that were defined in the beginning. These answers are later summarized in the discussion chapter.

### 4.1 Findings from qualitative research

The qualitative study carried out in the form of semi-structured interviews has resulted in the creation of six data clusters that are as follows:

-  Change drivers for prosumer driven 3d food printing
-  Challenges or constraints related to 3d food printing
-  Uncertainties regarding prosumer driven 3d food printing
-  Potential characteristics of a prosumer platform for 3d food printing
-  Potential customization parameters of a prosumer platform for 3d food printing
-  Potential archetypes and use-cases for prosumer driven 3d food printing

#### 4.1.1 Change drivers

Here, change drivers are the factors that call for the mainstreaming of prosumer driven 3d food printing. Various drivers identified from the literature and interview data are further classified under four broad global phenomena, namely technology, wellbeing, market megatrends, and sustainability, as illustrated in Figure 29.

With the digital revolution, people are increasingly becoming dependent on smart devices like cell phones and tablets. These gadgets currently play an important role in their daily life. People have also started using these smart devices for prosumer related activities. There are already digital food businesses that make use of smartphone platforms. These factors together with advancements in 3d printing are key technology drivers for prosumer driven 3d food printing. Another technology driver is the increasing open source accessibility. Knowledge is being shared digitally around the world for free, and is disrupting the current manufacturing paradigms. Interviews have suggested that this phenomenon would impact the 3d food printing scene of developing countries in the coming future.

Well-being is another key driver for prosumer driven 3d food printing. With the arrival of advanced health monitoring applications, people have become more conscious about what they consume. As identified from the literature, 3d food printing can help facilitate personalized nutrition. If a digital platform can combine the best of health monitoring and 3d food printing, which will create a lot of value to the fitness conscious generation. Natural and nostalgic consumption is another driver for 3d food printing. Ethical food products are being innovated, but their consumer desirability is still a question. 3d food printing along with a user-friendly platform can tackle this challenge. Other change driver identified includes the changing eating habits, and food convenience. Interviews suggested that the traditional 3 meal routine is slowly changing. Single meal per day combined with multiple snacking sessions is a growing trend. This also means that the snacks should be fresh and nutritious. 3d food printing would facilitate this if used with a prosumer platform.



Globalization and the dynamic markets associated with it are megatrends and change drivers for prosumer driven 3d food printing. These megatrends imply that businesses have to constantly innovate sustainable and consumer centric business models in order to stay successful. This according to the interviews holds true for the food industry too. Two other drivers under this category are growing global food demand, and increasing demand for a transparent food supply chain. Sustainability is another key driver. Global climate change, food miles, and food wastage are drivers for innovating sustainable business models in food industry. Two other drivers under sustainability are quest for alternate food ingredients, and the emerging trend towards buying and consuming locally produced ingredients.

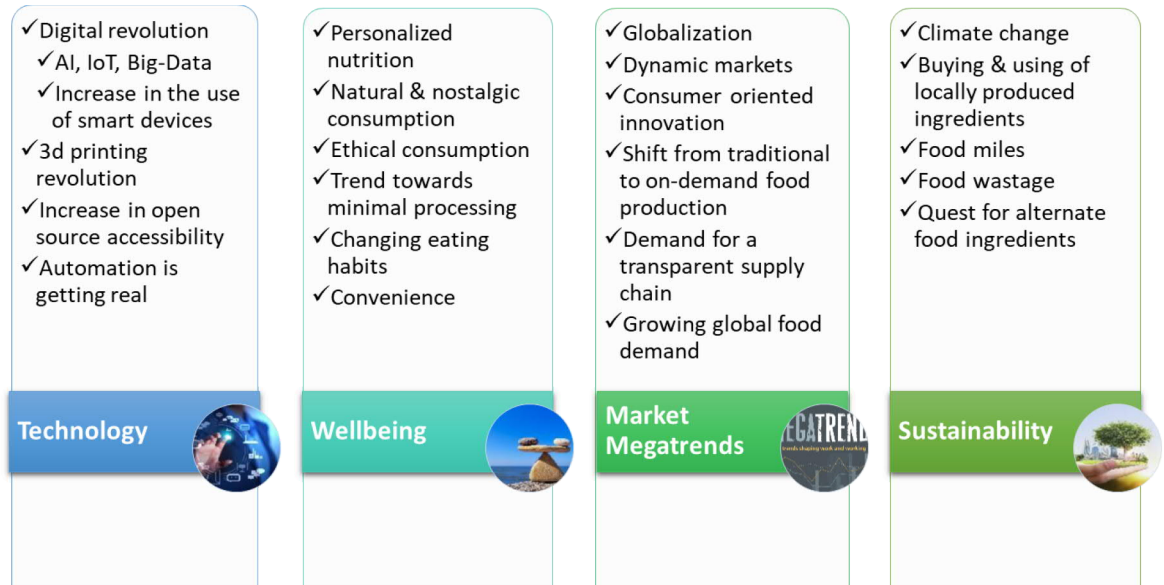


Figure 29: Change drivers for prosumer driven 3d food printing.

#### 4.1.2 Challenges/constraints

With all the potential in hand, 3d food printing does come with some challenges and constraints (see Figure 30). This data cluster is mostly drawn from the interview analysis. The challenges can be classified under five categories, which are technology, consumer acceptance, food science, quality control, and markets and business. From interviews with 3d printing experts, it is clear that speed and precision are 2 of the main constraints for 3d food printing at the moment. Also, multimaterial compatibility is a challenge for powder bed food printing technologies. Optimizing the extrusion width can be a challenge for FDM printers. Another big challenge identified is the scalability of the existing 3d food printer concepts. For creating functional value with 3d food printing, automation is essential. In case of most of the existing concepts, it is a challenge to facilitate automated processing and cooking activities. Other challenges related to 3d printing technology for food includes mixing of ingredients and moisture optimization. Mainstream consumer acceptance of 3d food printing will remain as a challenge until a true functional value can be demonstrated. Most of the food products require cooking or post-processing to be palatable. With the currently available technology, printing a ready to eat nutritious meal is challenging. This makes consumers to re-think about its value, except for the novelty aspect.

There are also some key challenges related to food science that prevents 3d food printing from becoming mainstream. Food products are mostly non-uniform mixtures made of multiple raw materials with complex rheological characteristics. Controlling and optimizing those characteristics are still a challenge. Another challenge in the field is in optimizing taste and texture of 3d printed food. Quality control is extremely important in case of food industry. Keeping 3d printed food clean and preserved especially when packaging is absent is a challenge. Some of the biggest challenges in 3d food printing are related to its market. The area is still under-researched, and therefore there is only limited market knowledge available now. It is a challenge for enterprises to find the right business models for prosumer driven 3d food printing. This in-turn makes convincing of investors a challenge.

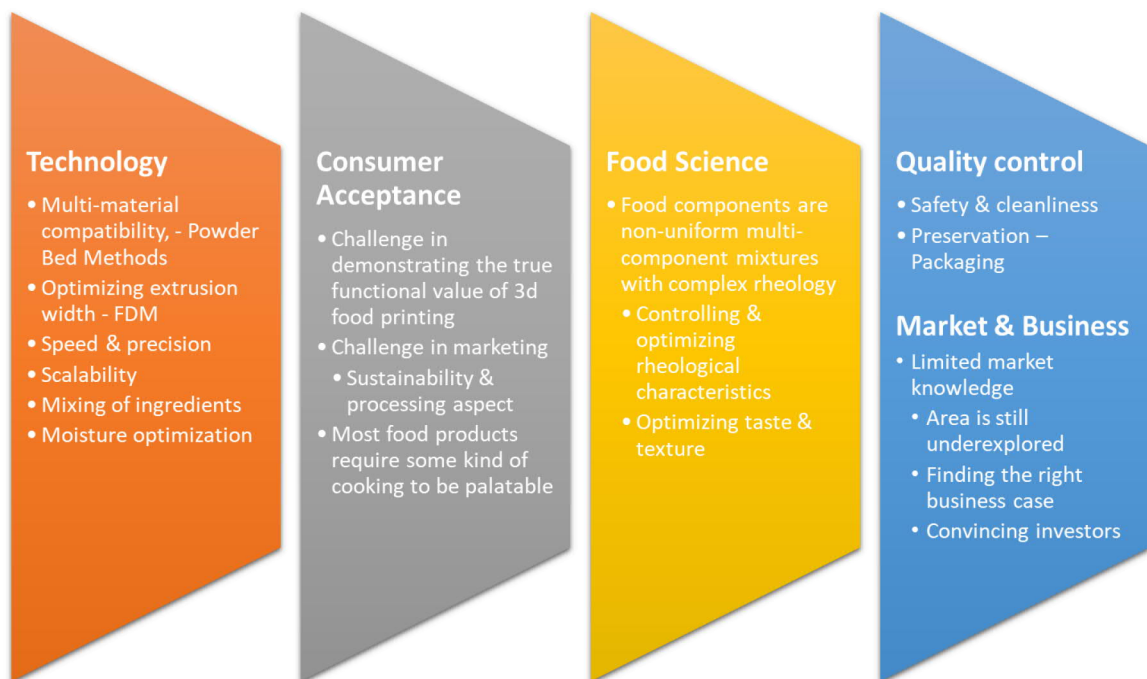


Figure 30: Challenges/constraints of prosumer driven 3d food printing.

### 4.1.3 Uncertainties

In addition to the challenges and constraints discussed above, there are some uncertainties (see Figure 31) that remains in the 3d printing ecosystem. These can be grouped into four categories, namely Market conditions, consumer perception, technology, and food delivery. Food industry is very price sensitive, therefore the overall viability of 3d food printing is uncertain now. The current applications of 3d food printing are targeted towards niche markets. It is uncertain when it could be taken to a mainstream market. It is also not fully sure how 3d printed food products will compete against traditionally produced food products. An interesting insight from one of the interview is that a prosumer platform for 3d food printing could potentially cause a cognitive overload, because of all the available customization possibilities. Another uncertainty regarding consumer perception is the term ‘printing’ in 3d food printing. It often gives a wrong impression to consumers. Also, there are still some questions regarding sustainability of 3d food printing, especially with respect to resource utilization and associated processing activities. Uncertainties regarding the technol-

ogy are mostly related to the scalability of existing 3d food printers. For example, technological feasibility and economic viability of post-processing/ cooking system integration. High volume production with a 3d food printer is still an uncertainty. Also, it is not sure if the advancements in traditional food production processes will impact 3d food printing innovation negatively. Regarding food delivery, possible variations in the look, feel, and taste along with possibility of errors are difficult to predict. Lastly, chemical, and biological degradation (spoilage) mechanism of 3d printed food products are unclear now.

Note that some of the most interesting uncertainties were tested using the survey, by taking it as hypotheses.

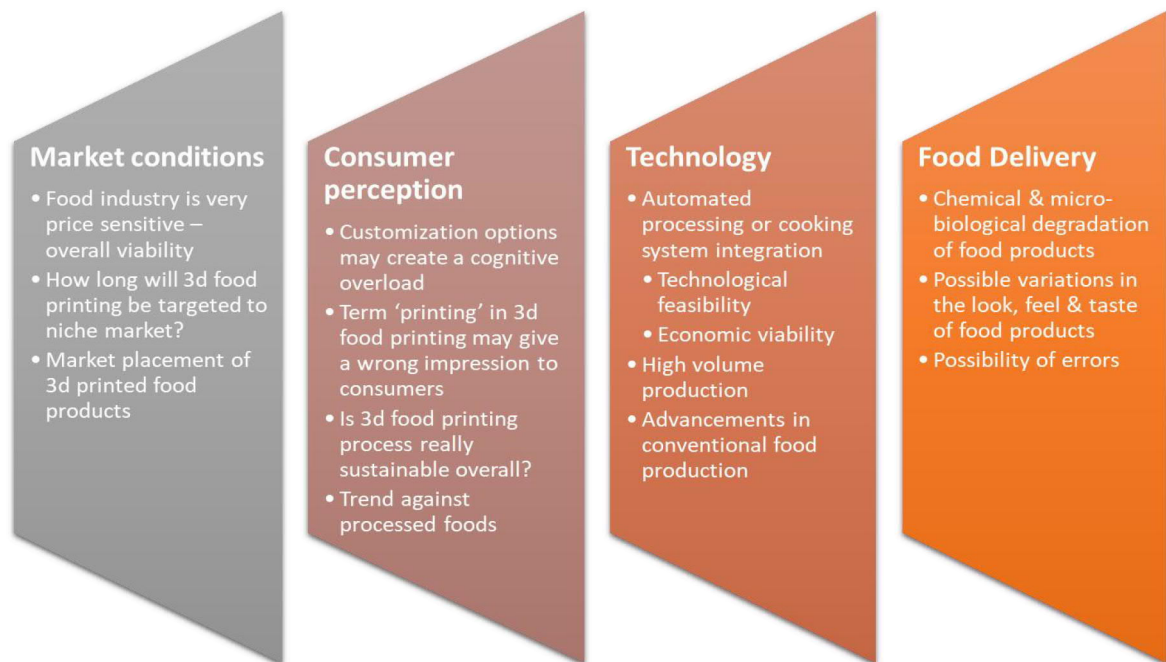


Figure 31: Uncertainties regarding prosumer driven 3d food printing.

#### 4.1.4 Characteristics of a prosumer platform for 3d food printing

It is clear from the interviews that the impact 3d food printers could have on the masses will be largely dependent on the digital platform being used. Many of the challenges and uncertainties of 3d food printing mentioned before can be tackled by having an effective prosumer platform. Some of the key characteristics identified for such a platform are as follows:

- Simple, and user-friendly interface
- Having optimal amount of customization options: Avoiding cognitive overload
- Ability to monitor the 3d food printing process
- Ability to monitor the available ingredients for 3d food printing
- Ability to monitor the total calories consumed
- Easy 3d design capabilities
- Easiness in accessing recipes
- Scalability: Easiness in adding-on features later
- Ability to take personal preferences into consideration
- Ability to take medical data in to consideration
- Ability for consumer to share recipes or 3d food designs to other consumers

#### 4.1.5 Customization parameters for prosumer driven 3d food printing

Various potential customization parameters for prosumer driven 3d food printing have been identified from the interviews. These are basically the parameters that the prosumers could potentially personalize using the digital platform while 3d food printing. The identified potential customization parameters are listed as follows:

- Nutritional content – macro & micro nutrients
- Portion size
- Ingredients and composition
- Flavour
  - How will the flavours be dispersed?
- Texture
- Appearance – shape
- Cooking method/ style
- Printing speed (related to printing time and quality)
- Packaging

#### 4.1.6 Potential use-cases for prosumer driven 3d food printing

Various prosumer archetypes and application areas for future 3d food printing systems were identified from interviews. These archetypes and application areas were coupled together to generate the following use-cases for prosumer driven 3d food printing.

##### 3d food printing vending machines in public places

**Redefining food convenience by combining public vending with prosumer driven 3d food printing**

Archetype: Commuters, office workers

Added value: Easy personalization and purchase of snacks using a digital platform, same time disrupting the distribution chain

Drivers: Changing eating habits, convenience, personalized nutrition, digital revolution, 3d food printing revolution

##### Digital gastronomy – Fine dining experience

**Bringing together technology, consumer preference and a unique dining experience!**

Archetype: Fine diners

Added value: Original food designs personalized for each customer, enhancing their overall eating experience

Drivers: Digital revolution, 3d food printing revolution, dynamic markets, consumer-oriented innovation

##### Personal nutrition for fitness enthusiasts

**Combining health and personal well-being with technology and food convenience**

Archetype: Fitness enthusiasts

Added value: Fast and easy access to personalized healthy snacks after fitness sessions

Drivers: Convenience, personalized nutrition, digital revolution, 3d food printing revolution

**3d printing food at home  
- Future of kitchen**

**Personalized home made meals utilizing interconnected devices and next generation 3d food printers**

---

Archetype: Home cook

Added value: Ability to cook remotely with the help of smart devices, thereby reducing the total time spent in kitchen. Additionally, it allows creating personalized healthy meals with locally grown natural ingredients.

Drivers: Changing eating habits, convenience, personalized nutrition, buying and consuming locally produced ingredients, alternate ingredients, natural consumption, automation, digital revolution, 3d food printing revolution

**Personalized nutrition for seniors**

**Enhancing the food experience of seniors without compromising their health, convenience and well-being.**

---

Archetype: Senior

Added value: Easy customization of macro & micro nutrients as well as food texture of meals aimed at seniors having chewing difficulties and special nutritional requirements. Prosumer driven 3d food printing will also impact their overall eating experience and hence their well-being.

Drivers: Personalized nutrition, convenience, 3d food printing revolution, digital revolution

**Personalized nutrition for patients in hospitals**

**Redefining hospital meal experience utilizing ICT and 3d food printing**

---

Archetype: Inpatient

Added value: Ability to create individualized meals for inpatients based on their medical data. This would in-turn improve their hospital experience overall.

Drivers: Personalized nutrition, convenience, natural & nostalgic consumption, 3d food printing revolution, digital revolution

**Personalized nutrition for students in universities**

**Redefining student meals at universities by combining ICT and prosumer driven 3d food printing**

---

Archetype: University students

Added value: Students can turn their personal designs into healthy meals, based on their nutrition requirements. They can do this remotely and hence reduce the total time spent at student restaurants (avoiding queues)

Drivers: Changing eating habits, convenience, personalized nutrition, automation, digital revolution, 3d food printing revolution

**Localized food production**

**De-centralized food production disrupting distribution chain, with out compromising on sustainability**

---

Archetype: Green consumers

Added value: Autonomous "green-food trucks" supplying personalized meals made with locally grown healthy ingredients will help reducing food miles and food wastage, thereby impacting on the overall sustainability of our food system.

Drivers: Climate change, food miles, food wastage, buying and consuming locally produced ingredients, personalized nutrition, digital revolution, 3d food printing revolution

**Personalized on-board meals in airplanes**

**Playful on-board meal experience enabled by prosumer driven 3d food printing**

---

Archetype: Frequent flyers

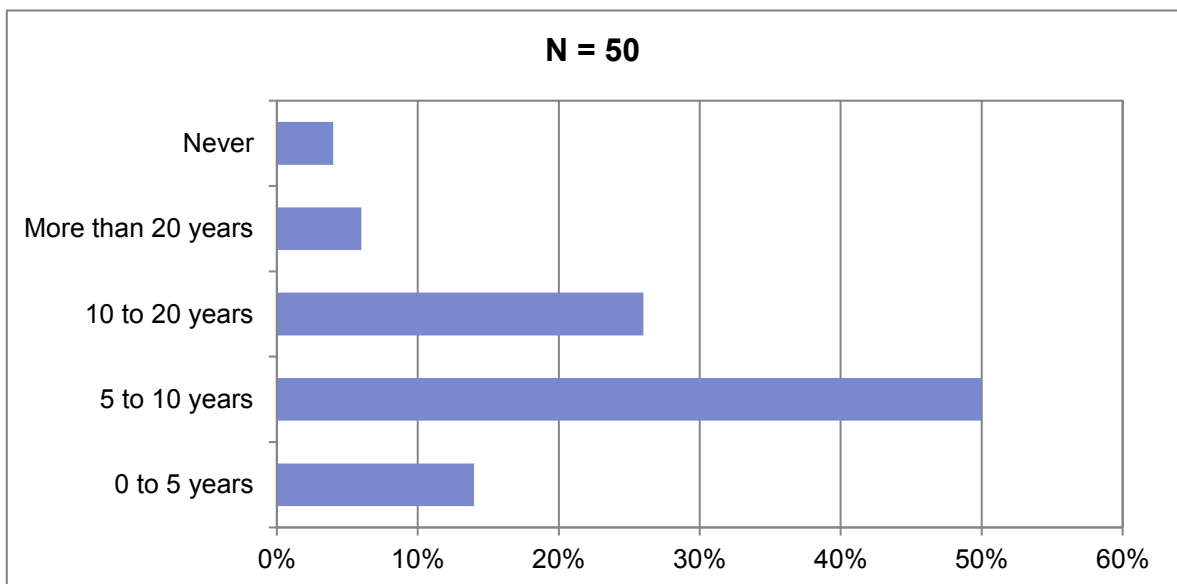
Added value: Instead of the same boring in-flight meals, passengers can create personalized food designs, utilizing a playful and user-friendly prosumer platform for 3d food printing. This would impact the overall flight experience of frequent fliers.

Drivers: Changing eating habits, convenience, personalized nutrition, automation, digital revolution, 3d food printing revolution

## 4.2 Findings from quantitative research

This section deals with the quantification of data, hypotheses, and use-cases obtained from the interview based qualitative research. Quantitative data collected from 50 survey participants are analysed here with the help of bar graphs. Stacked bar graphs are used to analyse questions with more complex structures. It is to be noted that ‘N’ in the graphs represents the sample size for that question.

3d food printing technology has been advancing little by little over the last 10 years. But there exists a lot of uncertainty regarding when it will be accepted as a mainstream technology. When the survey participants were asked this question, 50% of the respondents agreed that it will become a mainstream technology in 5 to 10 years. 26% of the respondents think that 3d food printing will be mainstream in 10 to 20 years. On the other hand, only less than 5% of the respondents feel that it will never be mainstream, and 6% of the respondents think that it will take more than 20 years (see Figure 32). It is important to note that mainstreaming of 3d food printing doesn’t really mean that it will replace traditional food fabrication processes, but rather means that it will catch the attention of general public.



*Figure 32: Mainstreaming of 3d food printing.*

Several hypotheses were generated from the qualitative results, mainly from the cluster about uncertainties. These were put as statements in the survey questionnaire for evaluating the agreement among experts. The first statement of the question, as shown in Figure 33 asks about the consumer acceptance of novel, sustainable food ingredients, which are presently being innovated. About 65% of the respondents agrees that prosumer driven 3d food printing will bring a positive impact on the consumer desirability of novel sustainable ingredients. Only 15% of the respondents disagrees to the statement. This means that alternate food materials including protein from insects, fava beans, and algae will have more consumer acceptance if produced using a prosumer driven 3d food printing platform. The second statement of the question (see Figure 33) was about whether an intuitive smartphone application better motivates consumers to utilize 3d food printing. It should be noted that here the intuitive smartphone application refers to the prosumer platform for 3d food printing. About 80% of the total respondents agrees that an intuitive digital platform will be a motivation for

consumers to utilize 3d food printing more. The third statement of the question (see Figure 33), that is whether the term ‘printing’ in 3d food printing gives a wrong impression to consumers, got an interesting response. About 30% of the total respondents strongly agrees that the term gives a wrong impression to consumers. The fact that only less than 20% of the respondents disagrees to this statement shows how much undesirability the term ‘printing’ in 3d food printing brings in. The next statement asked was whether 3d food printing is a sustainable process in general. While about 55% of the respondents agrees and 20% disagrees, more than 20% of the respondents chose neither agree nor disagree. Also, the response rate for this statement is comparatively less (see Figure 33). Thus, it can be inferred that even though 3d food printing can be described as a sustainable process, there are still some uncertainties related to it. It can also be said that 3d food printing will remain as a technology for niche applications in the future, since around 55% of the participants agrees to the statement (see Figure 33). The last statement of the question, was the easiest to analyse as 75% of the respondents agrees that the food industry is highly consumer driven (see Figure 33).

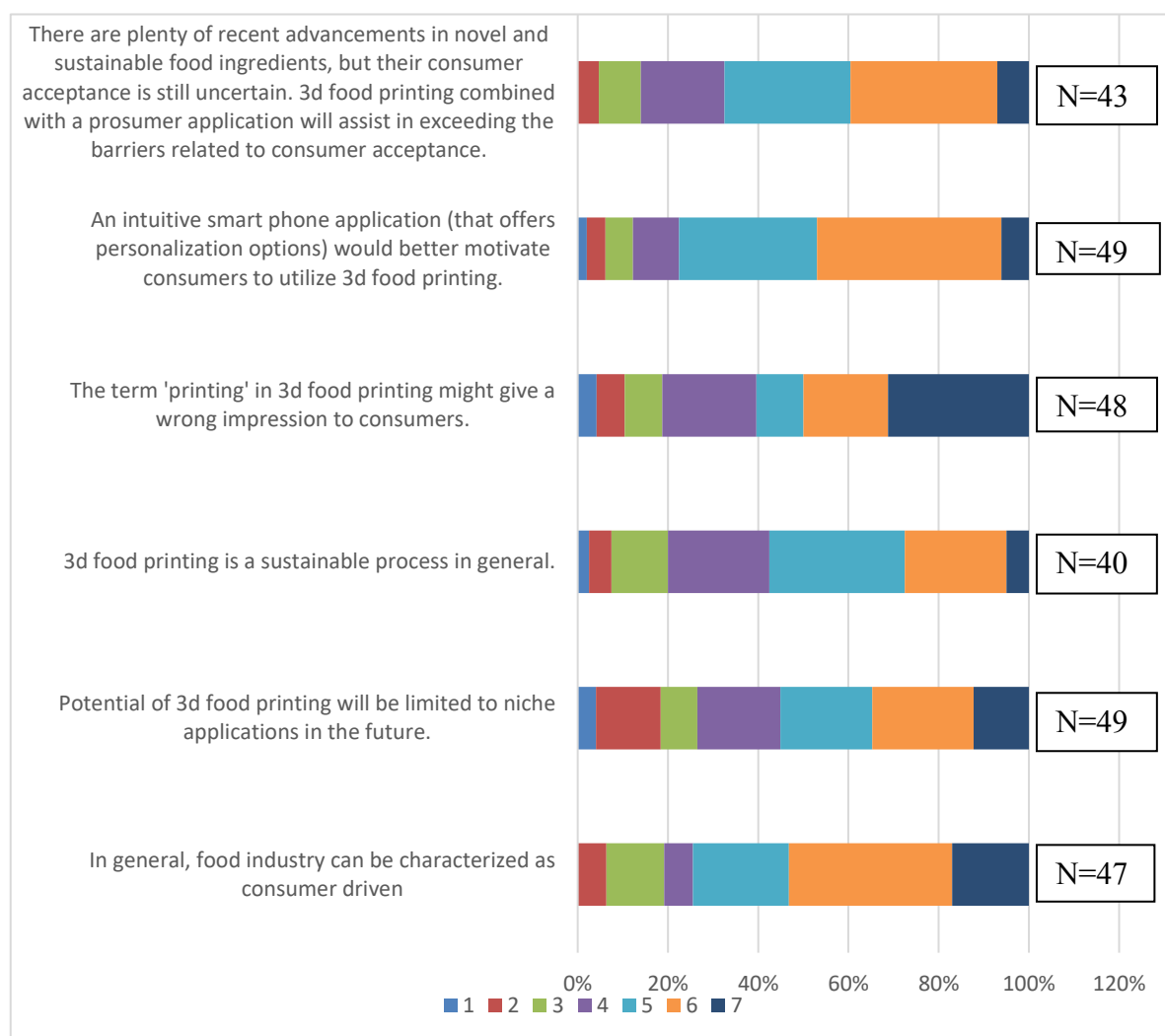


Figure 33: Evaluation of hypotheses from interviews.

The next question of the online survey deals with the identification of key characteristics of the prosumer platform (see Figure 34). It is clear from the graph that ability to take personal preferences into consideration is by far the most important characteristic of a prosumer platform for 3d food printing. 50% of the respondents agree that this trait is extremely important for such a digital platform. Another 40% feels that it's very important. The next important characteristic as per the graph is the access to recipes, followed by monitoring of available ingredients. Easy 3d design capabilities, and ability to take medical data into consideration are also found to be important. In general, it is clear from Figure 34 that most of the characteristics identified during interviews are significant.

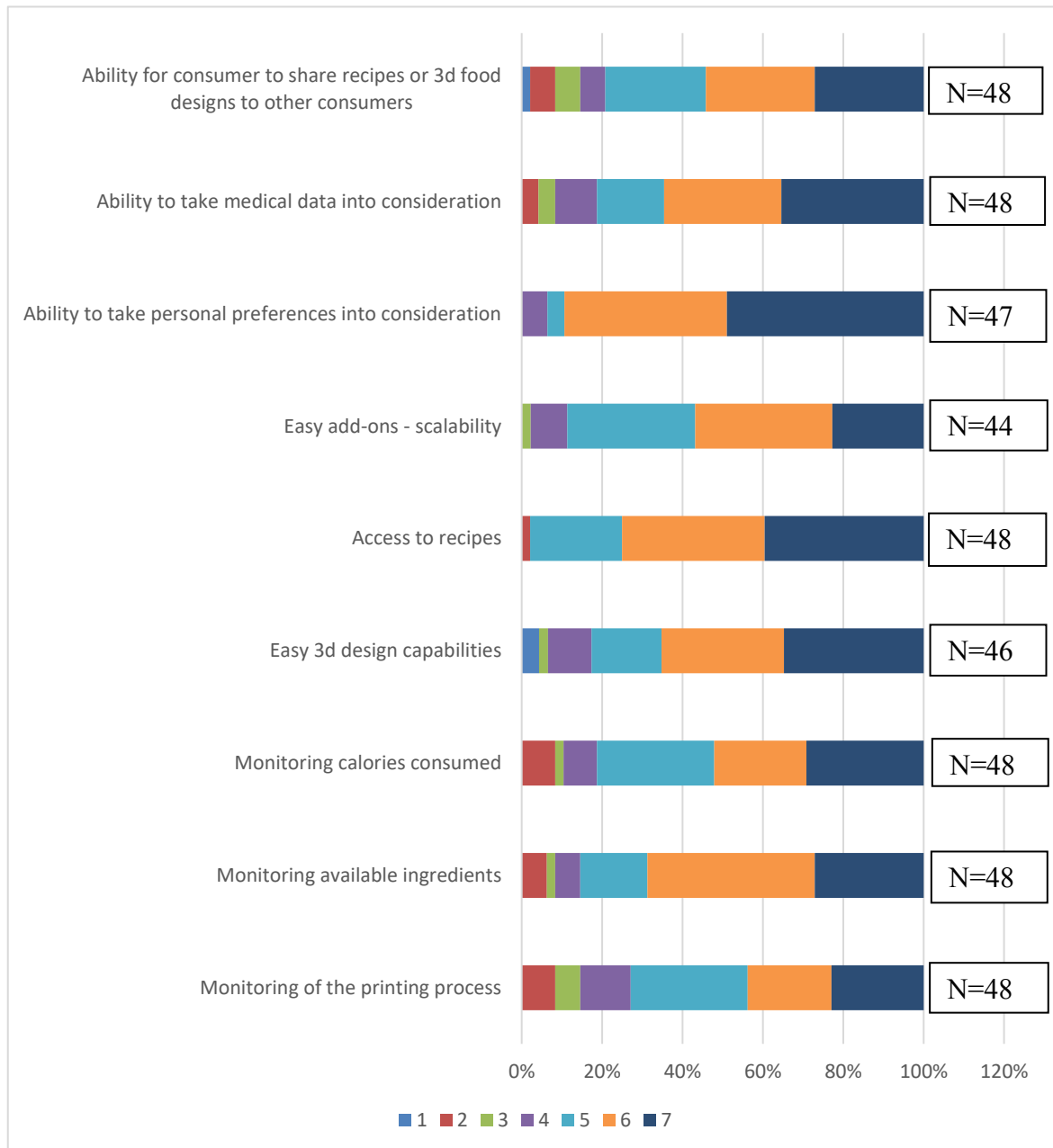


Figure 34: Key characteristics of a prosumer driven platform for 3d food printing.



The next two questions are related to the customization parameters for prosumer driven 3d food printing. Figure 35 illustrates responses about the desirability of customization parameters. It is clear from the graph that multiple ingredient options and flavour are two of the most desirable customization parameters, which half of the respondents consider extremely desirable. Controlling food texture and portion size are also found to be very desirable. On the other hand, cooking method customization is found to be less desirable for a prosumer driven 3d food printing platform.

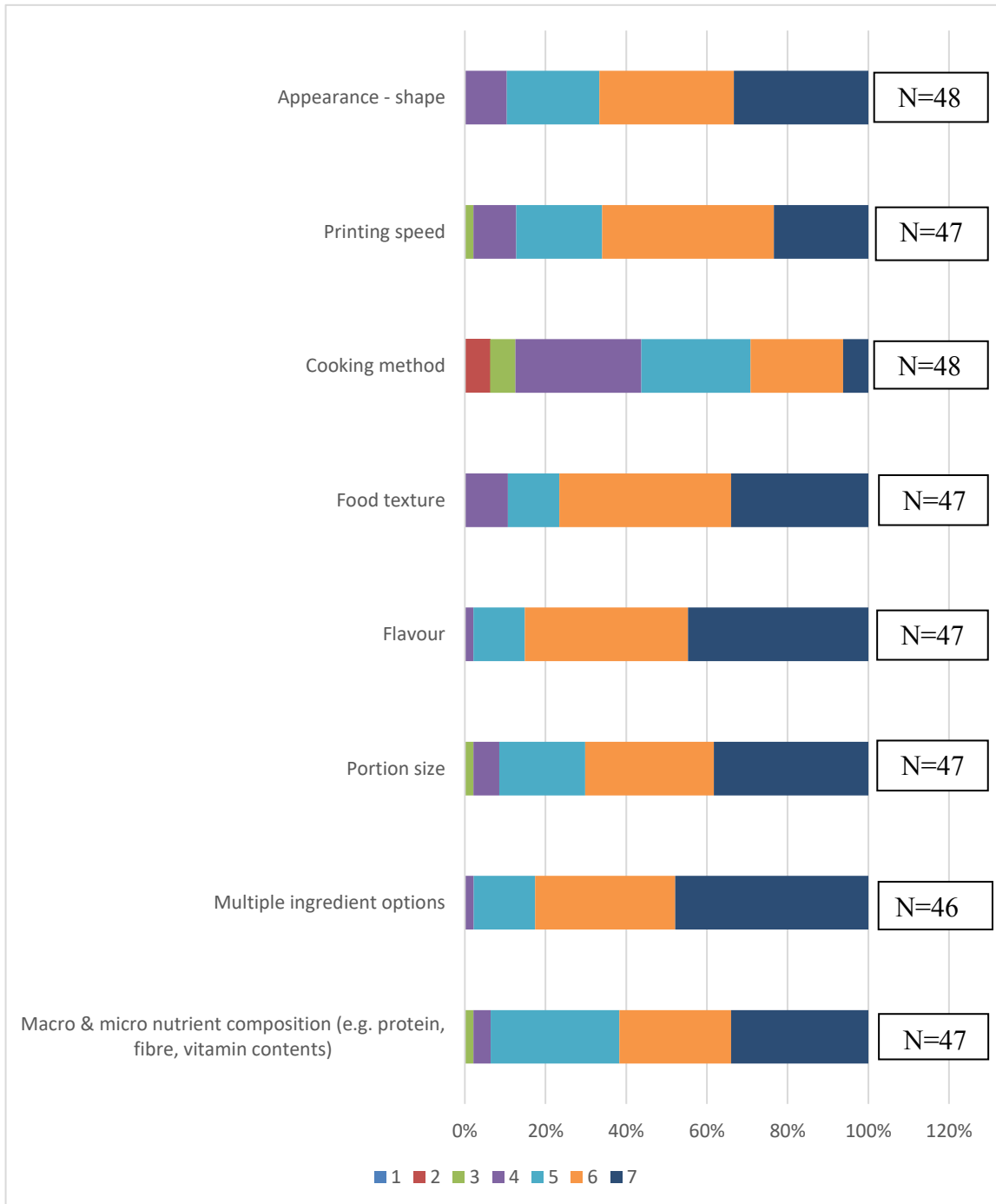


Figure 35: Desirability of customization parameters.

The number of respondents for the question related to the feasibility of customization parameters are comparatively less, with an average 10% no response rate. This could be mainly because of the uncertainties regarding existing 3d food printing technologies and their scalability. From Figure 36, portion size is found to be the most feasible customization parameter, which is also the most obvious one. It is followed by appearance and multiple ingredients option respectively. Controlling of macro & micro nutrients is found to be fairly feasible too. Customizing cooking method is the least feasible in the list. Customization of printing speed, food texture, and flavour are also found to be comparatively difficult.

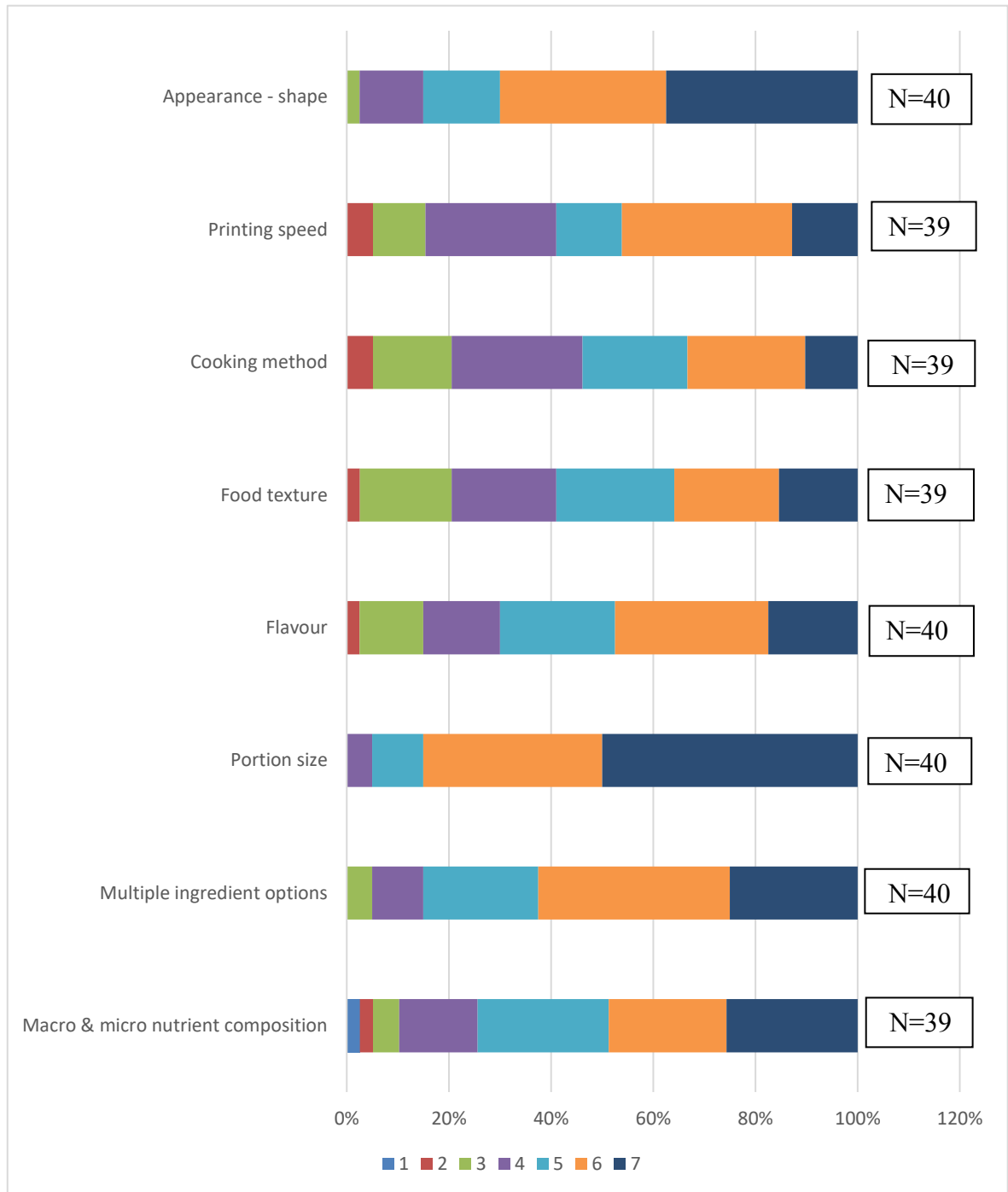


Figure 36: Feasibility of customization parameters.

The next two questions are about the potential use-cases, specifically related to its business potential and feasibility. From Figure 37, it is very clear that personalized nutrition for university students has a very low business potential. On the other hand, personalized nutrition for athletes, personalized nutrition for elderly, and that for patients in hospitals have high business potential. Digital gastronomy, i.e., utilizing prosumer driven 3d food printing in fine dining has the highest business potential of all use-cases listed. About 75% of the respondents agree that 3d food printing vending machine concept has a high business potential.

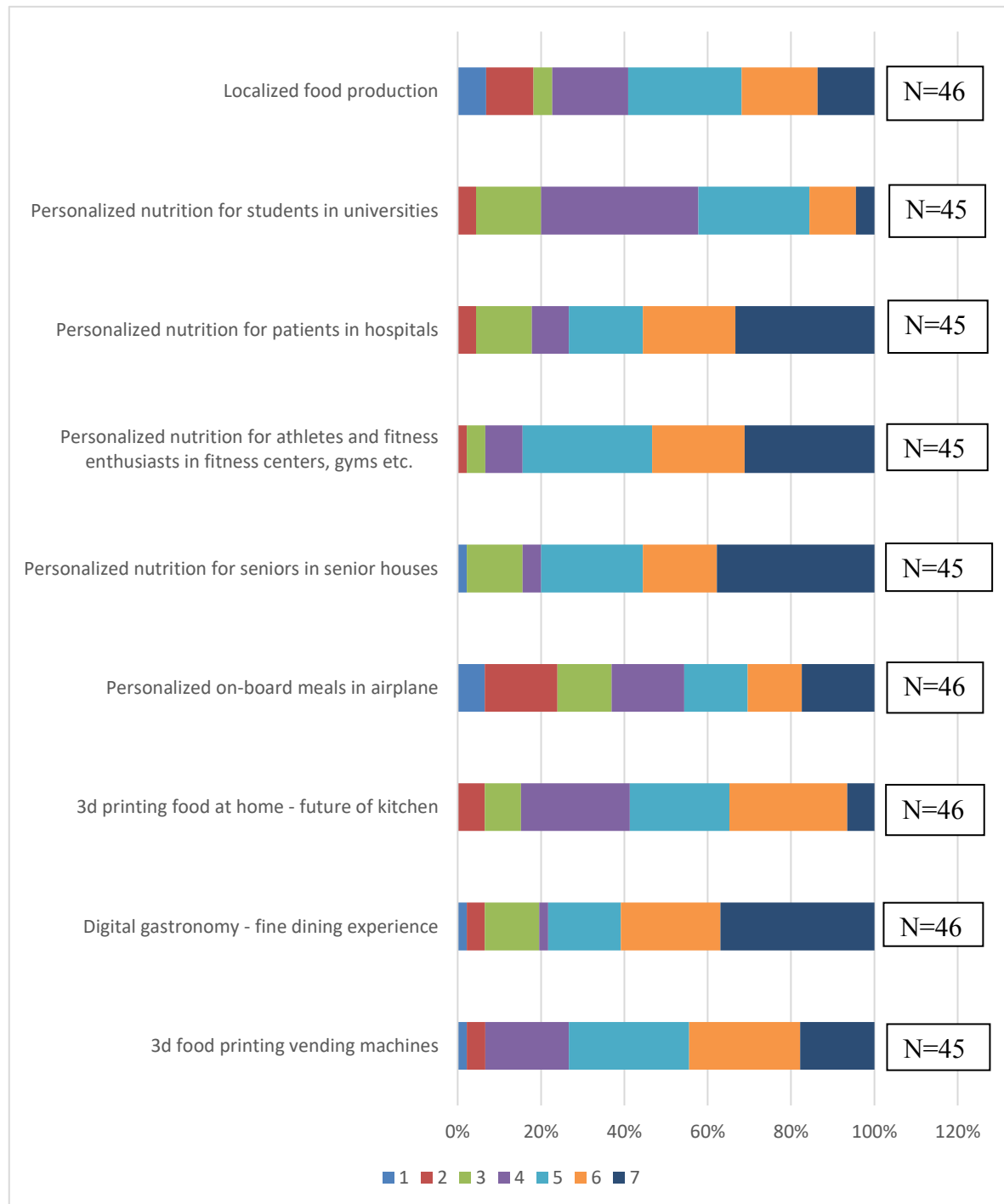


Figure 37: Businesses potential of use-cases.

In case of feasibility of the identified use-cases, the response is almost comparable to that of the previous question (Figure 38). Prosumer driven 3d food printing in fine dining is one of the most feasible concept. Other use-cases with high feasibility includes personalized nutrition in fitness centres and sports clubs, personalized nutrition for seniors, and personalized nutrition for patients in hospitals. 3d food printing vending machine concept is found to be a fairly feasible use-case. The least feasible concepts are personalized meals for university students and localized food production.

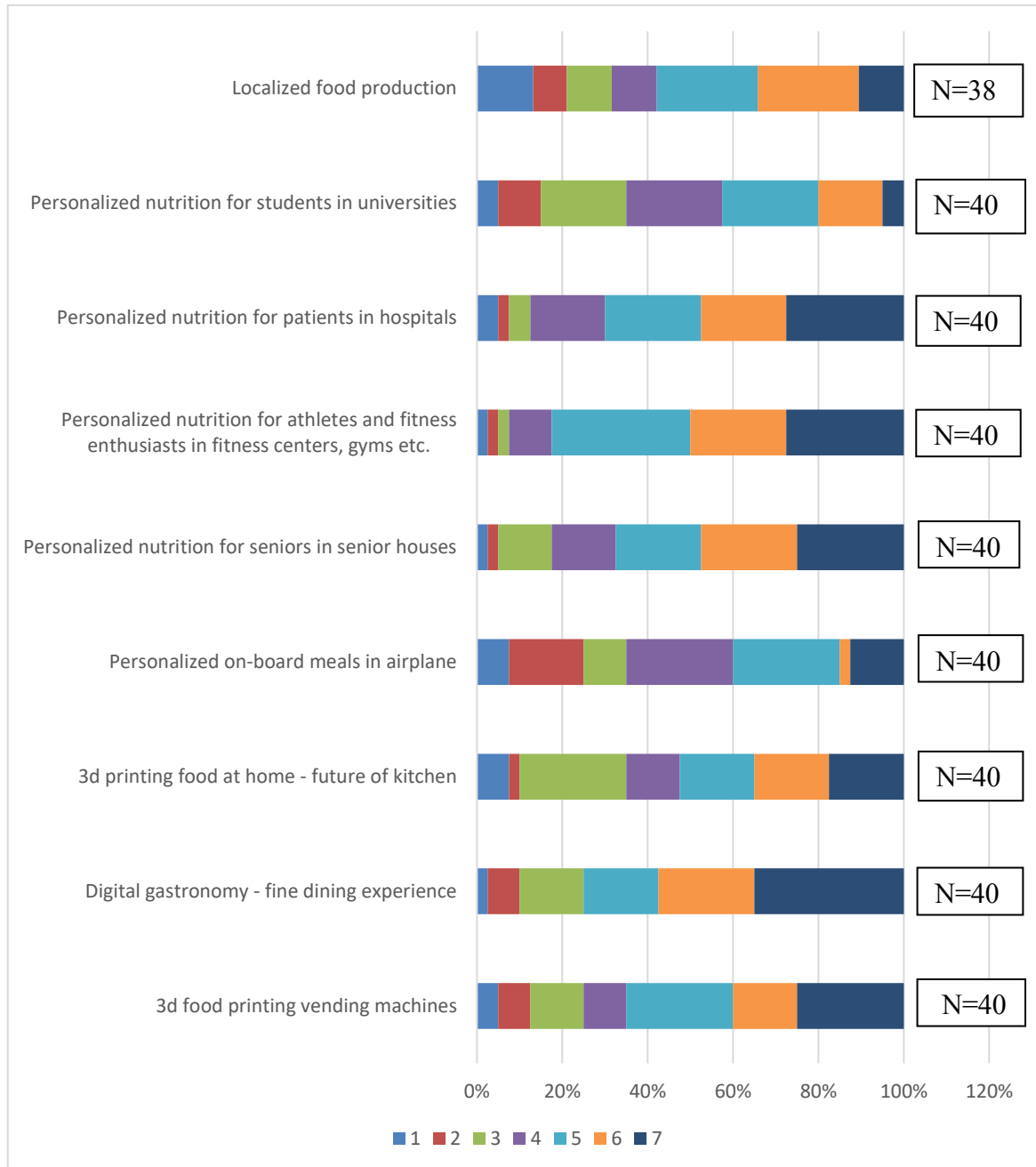


Figure 38: Feasibility of use-cases.

## 4.3 Further developments

Once the key characteristics, and key customization parameters of the prosumer driven 3d food printing platform were identified, prosumer work flow models are created for the 3-selected use-cases as illustrated in Figure 39, Figure 40, and Figure 41. These work-flow models illustrate how food prosumption is carried out using a digital platform (e.g. a smart phone application) and a 3d food printer. The 3 use-cases were selected based on its feasibility, business potential, and novelty value. 3d food vending is found to be a novel concept in the current 3d food printing scene, while having a business potential and feasibility less than personalized nutrition for elderly, and personalized nutrition for patients in hospitals. These 3 use-cases were further refined through the stakeholder workshop (see Appendix 3 and Appendix 4).

### 4.3.1 3d food printing vending machines

Vending machines are automated systems that delivers convenience goods like snacks, beverages, candies, and gums. Its current business models are mostly based on impulse purchasing of consumers. As identified from the interviews, there is a trend of changing eating habits. People are incorporating more snacking sessions to their daily routine, and moving away from a '3 meals per day' system. At the same time people are also conscious about the nutrient content of meals/snacks they consume. Here lies a great potential for prosumer driven 3d food printing enabled public vending machines. By making use of the digital revolution and 3d food printing revolution, this concept can facilitate easy personalization and purchase of snacks, disrupting the distribution chain. This use-case is targeted to daily commuters and office workers. Unlike the regular vending machines, 3d food printing vending machines shouldn't be targeted to impulse buyers, but for semi-public who value food convenience. Here, automation utilizing IoT, AI, Big Data etc. is a big factor in creating value, since most people may not spend a lot of time in planning what to print. Coffee shops, universities, and office spaces could be an entry market for this use-case, which can slowly be scaled to public libraries, metro stations, and other places. It is clear from the survey results and workshop that this concept has a lot of business potential. On the other hand, its technology feasibility is not very high. Related uncertainties and challenges includes cleaning and maintenance of vending machines, packaging possibility, speed of printing, and post-processing integration. In case of a connected system, personal data security is also a concern. This use-case if implemented, will be a big shift from the existing business models. Big players in food distribution sector can easily scale their business and reach new markets. It will also help food producers to brand their ingredients better. Also, food related logistics will be a lot simpler and cheaper in case of this concept. Here, the key collaboration should be between food producers, hardware producers, and prosumers.

Figure 39 illustrates the prosumer workflow for the 3d food vending concept. The workflow starts with prosumer creating an account for the 3d food vending application using a smartphone or a computer. Once the prosumer logs in, personal and medical data can be added, and the account can be linked to other digital platforms like social media. The landing page of the application shows all the available 3d food vending machines to select from. Some of the possibilities includes connecting to location services and tracking the commute pattern, or office routine. User can also create a list with their favourite vending machines. Next step is to choose the ingredients for 3d food printing. The application will allow real time monitoring of the available ingredients. Food templates like crunchy, creamy, salty etc.

may also be present for the user to choose from. Next the platform will automatically personalize the selection based on the user data. Here, manual personalization will also be possible, and user will be able to customize recipes, portion size, flavour, nutrition, and design. In the next step, user can select the printing time and collection time. Additionally, choices regarding storage and packaging can be made. Once the food design is confirmed, payment can be made using mobile banking for example. User will be able to monitor the printing process until the collection of the ordered food. 3d printed food can be collected from the selected vending machine by clicking on the collect button in the application interface. User will be prompted to pay if not done beforehand. Finally, the user may give feedback for the printed food, and save the food design as public or private for future use.

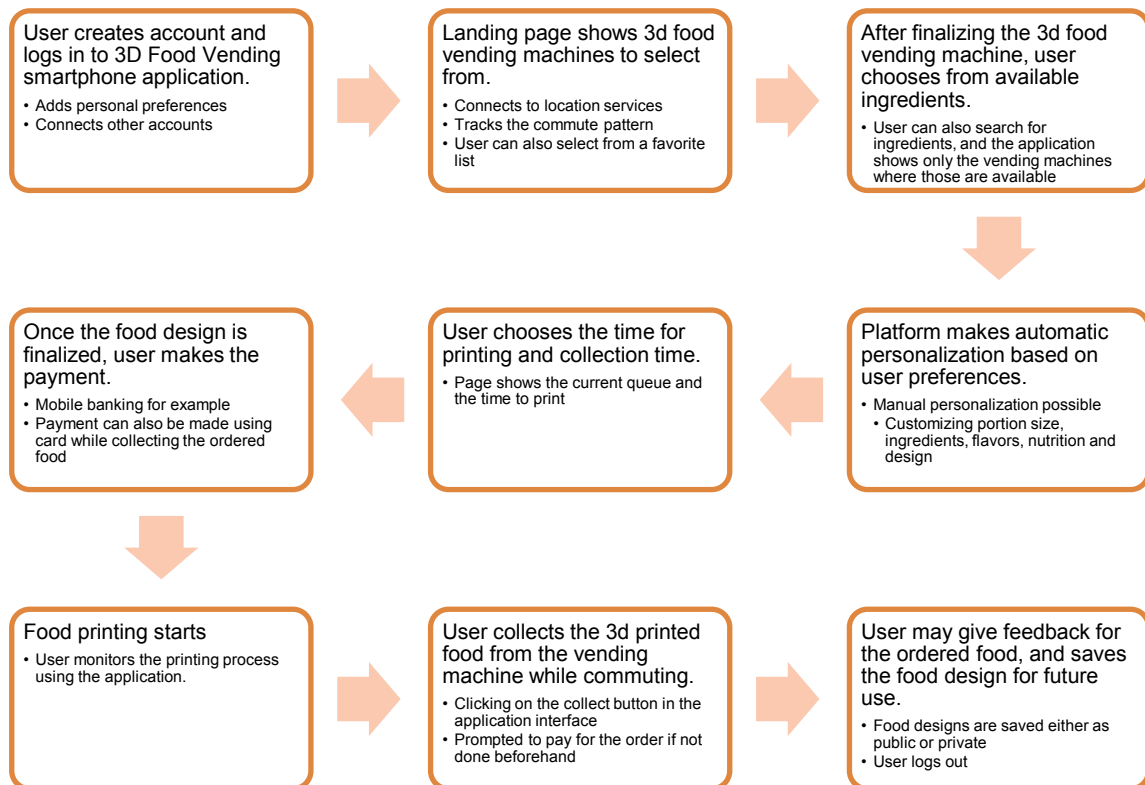


Figure 39: Prosumer work-flow for 3d food vending.

### 4.3.2 3d food printing in fine dining

Molecular gastronomy is all about creating a relationship between food and the consumer through different taste experiences. With the help of a 3d food printer and a prosumer platform, molecular gastronomy could become digital gastronomy. This would be an innovative business model for fine dining restaurants and Michelin star chefs. Digital recipes of star chefs could be made available globally, and a 3d food printer could fabricate a personalized meal based on it. Using such a system, same dessert can be designed differently for different individuals. Here, the main personalization aspect is design, i.e., shape, texture, and portion size. In fine dining the consumer usually pays for the overall eating experience and not just the food product. A playful digital interface could facilitate great user experience, as identified during the literature review. AI could be integrated to the platform in a later phase. This opens-up the possibility of updating recipes based on season and popularity. In the initial

phase, the printed food design will be post-processed manually, which could be automated later-on.

Figure 40 illustrates the prosumer workflow for 3d food printing in fine dining experience. Unlike the 3d food vending application, the user accesses the menu of fine dining restaurant from their web-based platform. An account may be created for storing personal preferences in the restaurant database. In this step, user can filter the available recipes manually based on popularity, price, season, allergies etc. Recipes that can be partially 3d printed, and traditionally cooked ones may also be available for the user to order from. If the user preference data is available for the platform, it will make an automatic personalization of the selected recipe. Otherwise, the user can manually personalize the food design. User can also upload designs, or create it on the intuitive platform with the help of templates. User may then make the order. Other orders can also be combined with it, for example, snacks, desserts, or beverages. The printing process will take place in front of the user, for example, on the table. This allows the user to follow the process live, and will add-on to the eating experience. Printing time can be monitored from the online platform. Finally, the user will make the payment for the order online or offline, and may give feedback for the recipe.

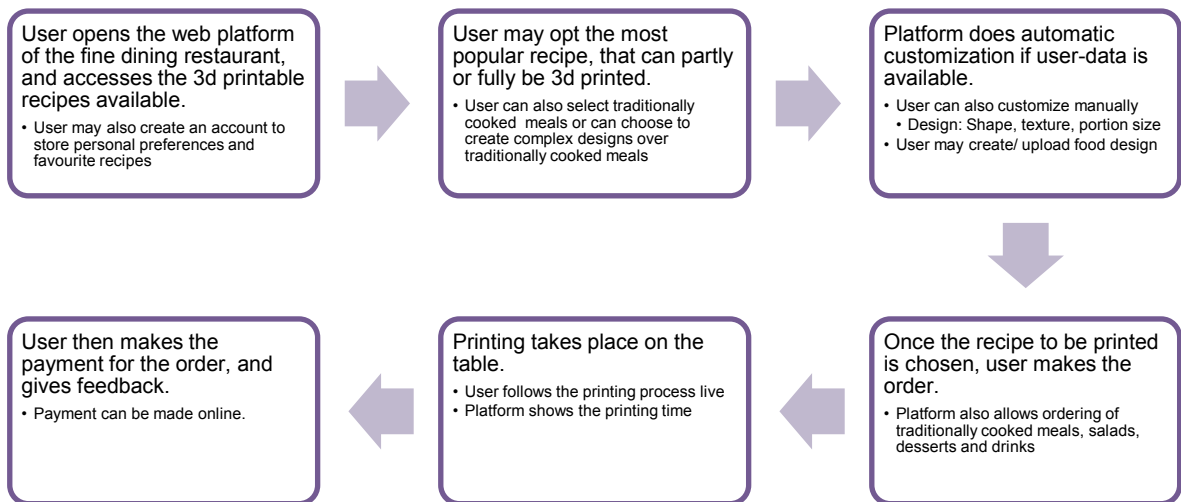
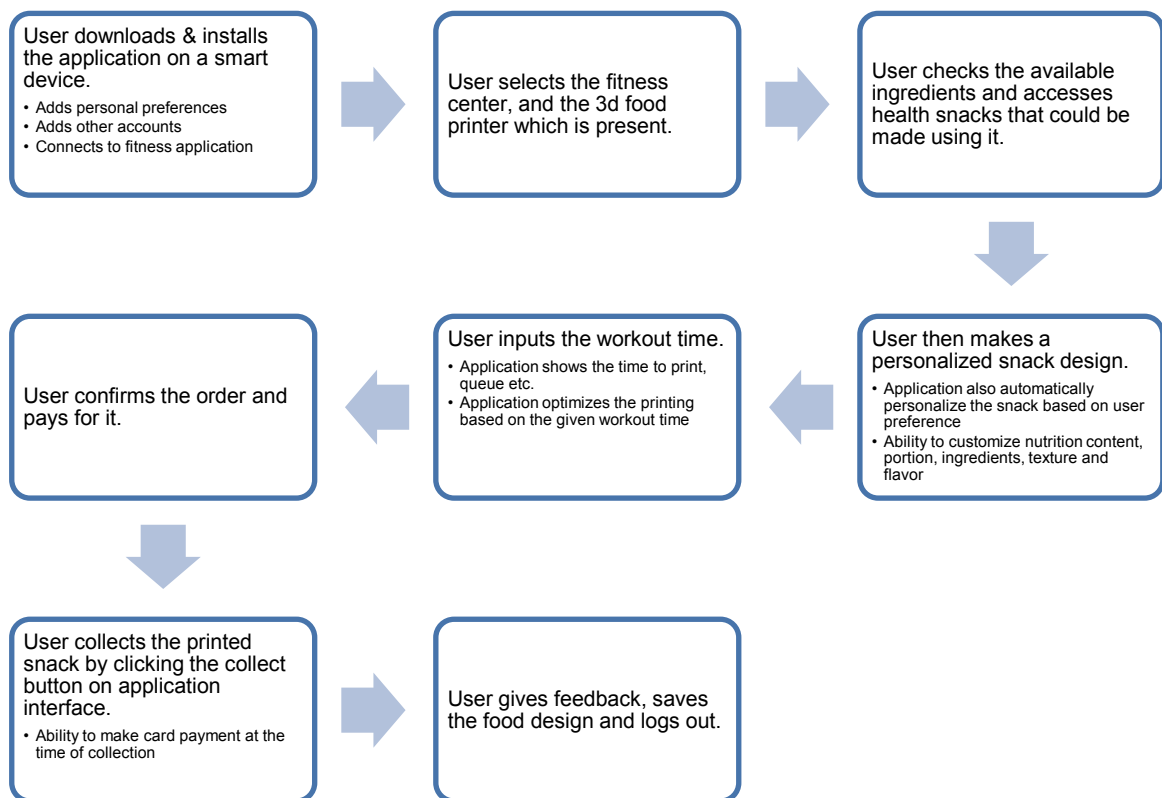


Figure 40: Prosumer work-flow for 3d food printing in fine dining.

### 4.3.3 3d food printing for fitness enthusiasts

From the literature review and interviews, it is found that 3d food printing is a great enabler of personalized nutrition. Also, self-quantification is becoming popular through personal tracking applications in smart devices. These two could be combined on a digital platform to facilitate fast and easy fabrication of personalized healthy snacks in fitness centres and sports clubs. Survey result suggests that this use-case has a high business potential, and is fairly feasible. An opportunity in the later phase is to integrate the 3d food printer with a vending machine. Since fitness enthusiasts aren't impulse buyers, there is a market potential here.

Figure 41 illustrates the prosumer flow diagram for this use-case. First step of the work-flow deals with the downloading and installing of the application on a smartphone. User may add personal preferences and other accounts to it. Connecting a fitness application with this digital platform is an option. In the second step, user will select the fitness centre and the available 3d food printer. The user can then check for the available food ingredients, and create personalized snack designs. A pre-designed recipe can be downloaded and personalized from the database if needed. Here the personalization will mainly be for nutrient content, portion size, ingredients, texture, and flavour. Utilization of sustainable alternate ingredients is a possibility in this use-case. Once the snack design is made, workout time can be inputted. The application will optimize the printing time based on the workout time. Queuing situation will also be shown on the interface. The order can then be conformed and paid for. User may also choose to pay at the time of collection. The 3d printed snack can be collected after the workout by clicking the collect button on the application interface. Lastly, the user may give feedback and save the food design as public or private.



*Figure 41: Prosumer work-flow for personalized nutrition in fitness centres.*



## 5 Discussion

In this chapter, the answers to the research questions are summarized, and practical implications of the results are put forth. The research limitations, and future directions are also discussed in this chapter.

### 5.1 Results and implications

This master's thesis was aimed at defining how to best utilize 3d food printing technology for facilitating food prosumption. To achieve this, three research questions were asked. The first question was about identifying the change drivers, constraints, and uncertainties regarding prosumer driven 3d food printing. This was achieved through an extensive literature review process, and semi-structured-expert interviews. Doing so has also produced an updated state of the art of food system, prosumption, and 3d food printing. The identified key drivers for prosumer driven 3d food printing were grouped under four global phenomena – technology, well-being, market megatrends, and sustainability. In technology, the key drivers for change are found to be digital revolution, and 3d printing revolution. Under wellbeing, the most important drivers are personalized nutrition, convenience, and changing eating habits. Most contributing market megatrends includes consumer oriented innovation, demand for a transparent supply chain, and shift from traditional centralized food production to localized food production. Sustainability related aspects like quest for sustainable alternate food ingredients, challenges related to food wastage, and emerging trend towards buying and consuming local goods are also set to impact the prosumer 3d food printing scene. Some key challenges in implementing prosumer driven 3d food printing includes limited market knowledge, optimization of rheological characteristics of food ingredients, multi-material compatibility, and lack of an integrated cooking/ processing system. Main uncertainties surrounding the topic were also identified and categorized. Most interesting ones were framed as hypotheses and tested during the quantitative study. The biggest uncertainty is regarding the market condition. Viability of prosumer driven 3d food printing in the mainstream market is highly uncertain. From the quantitative research, it was found that 3d food printing technology will take between 5 and 10 years to gain mainstream importance. On the other hand, this doesn't mean that 3d printed food will fully replace traditional food products, but suggests that the technology will attain more prominence among people. Its potential will continue to be for the niche markets, until a viable system is innovated.

The second research question was about defining the role of a prosumer platform for 3d food printing. The main objective was to identify the key characteristics, and customization parameters for a prosumer driven 3d food printing platform. The potential characteristics and parameters were first identified from interviews, and then tested using the survey. Five most important characteristics identified after the quantitative analysis are ability to take personal preferences into consideration, access to recipes, monitoring of ingredients, Easy 3d design capabilities, and ability to take medical data into consideration. In terms of key customization parameters, the most desirable ones include multiple ingredient options, flavour, controlling food texture, and portion size. On the other hand, controlling flavour, and food texture are found to be less feasible, along with printing speed. While integrating customization parameters to a prosumer platform, it is very important to keep it simple in the beginning, with 3 most desirable/feasible customization options for example. This will in-turn prevent the cognitive overload in prosumers, that a large amount of customization parameters could cause.

The final research question was to identify prosumer archetypes and use-cases for future 3d food printing systems. From the quantitative study, it was found that digital gastronomy – fine dining application has the most business potential as well as feasibility. 3d food printers are already being utilized in fine dining restaurants, but their potential is not utilized fully. They are now used only for creating complex shapes that are difficult and time consuming to make by hand. On the other hand, there is a wide array of opportunities available if combined with a prosumer platform. Doing so will not only facilitate an innovative marketing strategy, but also will enhance the food experience further. It offers the possibility to automate fine dining by enabling pre-preparation of food. It also helps creating a special connection with food through different taste experiences, in other words, fosters molecular gastronomy. Smaller businesses can create specialities of top chefs, creating a ‘Spotify’ of fine dining.

In addition to fine dining, personalized nutrition based use-cases including ‘food experience at senior homes’, ‘food experience at hospitals’, and ‘personalized snacks at fitness centres/sports clubs’ have substantial business potential, and are found to be feasible. A prosumer platform can embed a health monitoring/ fitness application in the case of fitness centre use-case. Here the added value is from gathering data. The concept could also boost the marketing and branding activities, fostering new business opportunities like sports nutrition for example. Compared to public spaces, fitness centres are usually associated with less impulse buying. This opens an interesting opportunity to integrate 3d food printing vending machines with personalized fitness snacks. The above-mentioned use-cases strikes a fine balance between innovativeness and feasibility. On the other hand, personalized meals on-board an airplane, and 3d food printing vending machines are much more disruptive in nature, but scores less in terms of feasibility.

The overall implication of the work is the need to strive towards food value chains that are connected, collaborative, data-driven, and transparent. Future food value chains with 3d food printing needs to be dynamic, multi-directional matrices connecting all the key actors. There should be continuous interaction between different actors, for example, interaction between prosumers and businesses, and interactions between different businesses who co-creates value. These futuristic value chains could be automated and better predicted by leveraging the latest ICT innovations like AI, IoT, and quantified self. It is hoped that technology and market limitations associated with 3d food printing will diminish in the coming future, thereby allowing food prosumers to get most out of the technology.

## **5.2 Challenges**

The challenges and limitations associated with this master’s thesis revolves around the methodology used. While mixed methods research methodology helped in getting the best out of qualitative and quantitative methods, planning and execution of the research was challenging. The execution of qualitative work along with the analysis took more time than expected. This was mainly because of the global scope of the study, and the time at which it was carried out. The interviews were conducted during summer 2017, and the fact that the summer vacation period in Finland and mainland Europe is different has made its planning a bit complicated. This has made the qualitative study to extend for more than 3 months. This also took a toll with regards to survey planning. The qualitative analysis was complicated mainly because of the amount and range of data collected from about 600 minutes of recorded interviews from 4 different countries. Choosing the most relevant data for the quantitative study was also challenging due to this reason. Even though the quantitative study helped in

collecting data from 13 different countries, Finnish respondents dominated the sample size. Also, majority of the respondents were academics or researchers. This is since the pool of respondents was created primarily based on the research papers that were studied during the literature review phase. Workshop execution was another challenge because there were 14 participants in 3 groups, but only one facilitator to control the process. Additionally, the workshop was really time intensive as it lasted only for 2 hours. Analysis of the use-cases, especially the first one was challenging due to this time limitation. Once the participants understood what to do after the first analysis, process was greatly improvised for the next 2 use-cases. One aspect that was missing during this research work is direct interaction with the end-users. While the process followed, i.e., double diamond process, prompted the researcher to obtain data from a wide range of sources, a direct consumer study in the form of focus groups was absent. The concepts developed were also not tested with the real end-users. But it is to be noted that the defined scope of this master's thesis was limited to collecting data from industry experts, and researchers.

### **5.3 Future directions**

As mentioned in the Preface, this master's thesis is carried out as a part of a bigger Tekes project, 3D Surprise. The thesis output will be utilized by the upcoming work-package of 3D Surprise, which involves consumer research in the form of focus groups. This is the key reason for omitting end-user research from the scope of this master's thesis. The quantitative study as part of the thesis has evaluated the use-cases from a feasibility and viability point of view. According to Ideo (IDEO, 2009), experience innovation comes at the intersection of technological feasibility, economic viability, and consumer desirability. Hence, supplementing the expert data with consumer data is crucial for industries to understand the true innovative potential of identified use-cases. Another important step is to create 3d food printing machine concepts specifically for the identified use-cases. The machine concept here refers to the combination of software and hardware platform associated with each of the use-cases. The software platform is defined as part of this thesis, with regards to key characteristics and key customization parameters. Next step should be the feasibility investigation of most desirable food ingredient mixtures, and choosing of the right 3DP technology for it. Also, the actors from the value chain who are associated with the identified use-cases could further develop the concept by their own, and work towards leveraging it in their value offerings.

## 6 Conclusions

Digital platforms are important drivers for creating a captivating user-experience in today's world. They are found to have a great influence on user-acceptance of a product or technology. The present-day specialized goods manufacturing sector effectively combines digital platforms and 3d printing technology to enable high-level prosumption. On the other hand, food industry has not exploited the ongoing prosumption revolution yet. This situation could change if newly emerging 3d food printing technologies leverage the potential that digital platforms offers. The fundamental goal of this master's thesis was to analyse and understand the current state of 3d food printing, and to define characteristics and touch-points of a prosumer platform for it. The research also aimed at generating prosumer archetypes and use-cases for future 3d food printing systems.

The thesis started with an extensive literature review exploring food value chains, prosumption, and 3d food printing. These three areas formed the research themes for the theses, which were utilized in data collection. The research followed a mixed method approach in which 15 experts from 4 countries were interviewed first. The analysed interview results were used as input for an online survey. The survey received a positive response with 50 experts participating from 13 countries around the world. The survey data was used to generalize the interview findings. The concepts developed were further refined at a stakeholder workshop with 14 participants from various fields related to the topic.

Quantified data shows that an ideal prosumer platform for 3d food printing should be able to take personal preferences as well as medical data into consideration while facilitating food fabrication. It should also have easy access to recipes and intuitive 3d design capabilities for the prosumers. Real time monitoring of food raw materials is also found to be important. Selecting from multiple ingredients, manipulating flavour, controlling food texture, and choosing portion size are found to be the most significant customisation parameters for a prosumer driven 3d food printing platform. On the other hand, it is important to not to overwhelm prosumers with a huge amount of customization options and thereby creating a cognitive overload.

It is found that prosumer driven 3d food printing will compliment recent innovations related to sustainable alternate ingredients. Also, a user-intuitive platform for 3d food printing will motivate more people to engage in food prosumption. While the technology is predicted to gain prominence in the next 5 to 10 years, its applications will continue to be confined to niche areas. The most potential use-cases identified includes prosumer driven 3d food printing in fine dining restaurants, personalized healthy snacks for fitness enthusiasts, personalized nutrition in senior homes and hospitals. Prosumer driven 3d food printing vending machine concept is found to be highly disruptive, despite the uncertainties regarding its implementation feasibility.

Findings of this thesis should help the food sector to understand the potential of prosumer driven 3d food printing in disrupting value chains, and tackling societal, economic, and environmental issues. Its will enable easy personalization of food with no compromise in nutrition, giving a central role for consumers in the food system. Adoption of the selected use-cases should help generating a value chain that is connected, collaborative, data driven, and transparent. In short, an effective utilization of prosumer driven 3d food printing will support the creation of a sustainable food ecosystem.

## References

Alec (2015) *XYZPrinting shows off their \$500 3D Food Printer at CES 2015 in Las Vegas*, *3ders.org*. Available at: <https://www.3ders.org/articles/20150106-xyzprinting-shows-off-their-3d-food-printer-at-ces-2015-in-las-vegas.html> (Accessed: 24 November 2017).

Alec (2016) *Have a 3D printed frozen space pizza sent to your home through Kickstarter*, *3ders.org*. Available at: <https://www.3ders.org/articles/20160316-have-a-3d-printed-frozen-space-pizza-sent-to-your-home-through-kickstarter.html> (Accessed: 24 November 2017).

Anderson, C. (2012) *Makers: The New Industrial Revolution*.

Andrews, D., Research Professor, D., Nonnecke, B., Professor, A. and Preece, J. (2003) 'Conducting Research on the Internet: Online Survey Design, Development and Implementation Guidelines', *International Journal of Human-Computer Interaction*, 16(2), pp. 185–210. Available at: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.91.4972&rep=rep1&type=pdf> (Accessed: 26 November 2017).

ASTM-International (2015) 'Standard Terminology for Additive Manufacturing Technologies', *ASTM F2792-10e1*. doi: 10.1520/F2792-10E01.

Avery, M. L., Hamamoto, B., Kreit, B. and Smith, S. (2014) *Seeds of Disruption: How Technology is Remaking the Future of Food, A Global Food Outlook: Map of the Decade 2013 – 2023*. Institute for the Future. Available at: <http://www.iftf.org/maps/seeds-of-disruption/seeds-of-disruption-map/>.

Bardenstein, A., Dunwoody, G., Cinelli, P., Valetton, J., Amato, G., Ostergaard, S., Langer, D., Langer, M., Landa, S., Wagtberg, H., Webb, S., Kuck, M. and Forstner, S. (2014) 'Packaging for Personalized Food for Nutrition of Elderly Consumers Made Using Rapid Manufacturing', in *19th IAPRI World Conference on Packaging*. Melbourne, pp. 358–367.

Beer, D. and Burrows, R. (2010) 'Consumption, Prosumption and Participatory Web Cultures: An introduction', *Journal of Consumer Culture*, 10(1), pp. 3–12. doi: 10.1177/1469540509354009.

Begley, S. (2014) *Nestlé Is Developing an Instant-Nutrient Food Machine*, *TIME Health*. Available at: <http://time.com/2912509/nestle-is-developing-an-instant-nutrient-food-machine/> (Accessed: 22 November 2017).

Benedict (2017) '3D printer that turns nano-cellulose into nutritious meals could be part of your kitchen in 5 years | 3D Printer News & 3D Printing News', *3ders.org*. Available at: <http://www.3ders.org/articles/20171025-3d-printer-that-turns-nano-cellulose-into-nutritious-meals-could-be-part-of-your-kitchen-in-5-years.html> (Accessed: 16 November 2017).

Van Bommel, K. (2014) '3D Food Printing', *TNO*.

Bonny, S. P. F., Gardner, G. E., Pethick, D. W. and Hocquette, J.-F. (2015) 'What is

artificial meat and what does it mean for the future of the meat industry?', *Journal of Integrative Agriculture*, 14(2), pp. 255–263. doi: 10.1016/S2095-3119(14)60888-1.

Brewer, J. and Hunter, A. (1989) *Multimethod research: a synthesis of styles*. Sage Publications (Sage library of social research). Available at: <https://books.google.fi/books?id=bbAOAQAAMAAJ>.

CandyFab (2006) *The CandyFab Project*. Available at: <http://candyfab.org/> (Accessed: 24 November 2017).

Chesney, R. (2014) *Thought for the Future of Food, Institute for the Future*. Available at: <http://www.iftf.org/future-now/article-detail/thought-for-food/> (Accessed: 21 June 2017).

Choc Edge (2011) *Choc Creator*. Available at: <http://chocedge.com/> (Accessed: 24 November 2017).

Chowbotics Inc. (2017) *Sally - Chowbotics*. Available at: <http://www.chowbotics.com/sally/> (Accessed: 3 November 2017).

Cohen, D. and Crabtree, B. (2006) 'Semi-structured Interviews', *Qualitative Research Guidelines Project*. Available at: <http://www.qualres.org/HomeSemi-3629.html> (Accessed: 25 November 2017).

Cohen, D. L., Lipton, J. I., Cutler, M., Coulter, D., Vesco, A. and Lipson, H. (2009) 'Hydrocolloid Printing: A Novel Platform for Customized Food Production', in *20th Annual International Solid Freeform Fabrication Symposium*. Austin, Texas, pp. 807–817.

Creswell, J. W., Sobczak, A. J. and Lee, M. (2003) 'Research Design: Qualitative, Quantitative and Mixed Methods Approaches', 7.

Crump, S. S. (1992) 'Apparatus and Method for Creating Three-Dimensional Objects', *US Patent 5,121,329*, p. 15.

Curry, L. A., Krumholz, H. M., O'Cathain, A., Plano Clark, V. L., Cherlin, E. and Bradley, E. H. (2013) 'Mixed methods in biomedical and health services research.', *Circulation. Cardiovascular quality and outcomes*. American Heart Association, Inc., 6(1), pp. 119–23. doi: 10.1161/CIRCOUTCOMES.112.967885.

David (2017) *3D printing vegetables could lead to healthier children, new study suggests, 3ders.org*. Available at: <http://www.3ders.org/articles/20170725-3d-printing-vegetables-could-lead-to-healthier-children-new-study-suggests.html> (Accessed: 29 July 2017).

Design Council (2005) *The Design Process: What is the Double Diamond?* Available at: <http://www.designcouncil.org.uk/news-opinion/design-process-what-double-diamond> (Accessed: 24 November 2017).

Design Council (2007) 'Eleven lessons: Managing design in eleven global brands', *A study of the design process*. Available at: [http://www.designcouncil.org.uk/sites/default/files/asset/document/ElevenLessons\\_Design\\_Council\\_\(2\).pdf](http://www.designcouncil.org.uk/sites/default/files/asset/document/ElevenLessons_Design_Council_(2).pdf) (Accessed: 24 November 2017).

- FAO (2017) *The future of food and agriculture: Trends and challenges*. Rome. Available at: <http://www.fao.org/publications/card/en/c/d24d2507-41d9-4ec2-a3f8-88a489bfe1ad/>.
- Fox, S. (2014) ‘Potential of virtual-social-physical convergence for project manufacturing’, *Journal of Manufacturing Technology Management*, 25(8), pp. 1209–1223. doi: 10.1108/JMTM-01-2013-0008.
- Fox, S. (2016) ‘Domesticating artificial intelligence: Expanding human self-expression through applications of artificial intelligence in prosumption’, *Journal of Consumer Culture*, 0(0), pp. 1–15. doi: 10.1177/1469540516659126.
- Fox, S. (2017) ‘Mass imagineering, mass customization and mass production: Complementary cultures for creativity, choice and convenience’, *Journal of Consumer Culture*, pp. 1–15. doi: 10.1177/1469540517705945.
- Gartner Inc. (2014) *Gartner’s 2014 Hype Cycle for Emerging Technologies Maps the Journey to Digital Business, Hype Cycle for Emerging Technologies*. Available at: <http://www.gartner.com/newsroom/id/2819918> (Accessed: 16 May 2017).
- Gartner Inc. (2017) *Gartner Identifies Three Megatrends That Will Drive Digital Business Into the Next Decade, Hype Cycle for Emerging Technologies*. Available at: <http://www.gartner.com/newsroom/id/3784363> (Accessed: 16 August 2017).
- Gausemeier, J., Echterhoff, N. and Wall, M. (2012) ‘Thinking ahead the Future of Additive Manufacturing – Analysis of Promising Industries’, *University of Paderborn Direct Manufacturing Research Center*, p. 103. Available at: [https://www.rtejournal.de/ausgabe9/3355/view?set\\_language=de](https://www.rtejournal.de/ausgabe9/3355/view?set_language=de).
- Gebler, M., Schoot Uiterkamp, A. J. M. and Visser, C. (2014) ‘A global sustainability perspective on 3D printing technologies’, *Energy Policy*. Elsevier, 74(C), pp. 158–167. doi: 10.1016/j.enpol.2014.08.033.
- Godfray, H. C. J., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Nisbett, N., Pretty, J., Robinson, S., Toulmin, C. and Whiteley, R. (2010) ‘The future of the global food system’, *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1554), pp. 2769–2777. doi: 10.1098/rstb.2010.0180.
- Godoi, F. C., Prakash, S. and Bhandari, B. R. (2016) ‘3d printing technologies applied for food design: Status and prospects’, *Journal of Food Engineering*. Elsevier Ltd, 179, pp. 44–54. doi: 10.1016/j.jfoodeng.2016.01.025.
- Gold, T. (2014) *Eating delicious 3D candy printed by a ChefJet - The Verge, The Verge*. Available at: <https://www.theverge.com/ces-2014/2014/1/7/5285628/3d-systems-chefjet-pro-sweet-3d-printer-candy-hands-on> (Accessed: 24 November 2017).
- Greene, J. C., Caracelli, V. J. and Graham, W. F. (1989) ‘Toward a conceptual framework for mixed methods evaluation design’, *Educational Evaluation and Policy Analysis*, 11, pp. 255–274.
- Hall, L. (2013) ‘3D Printing: Food in Space’. Brian Dunbar. Available at: [https://www.nasa.gov/directorates/spacetech/home/feature\\_3d\\_food.html](https://www.nasa.gov/directorates/spacetech/home/feature_3d_food.html) (Accessed: 21

November 2017).

Hao, L., Mellor, S., Seaman, O., Henderson, J., Sewell, N. and Sloan, M. (2010) 'Material characterisation and process development for chocolate additive layer manufacturing', *Virtual and Physical Prototyping*. Taylor & Francis, 5(2), pp. 57–64. doi: 10.1080/17452751003753212.

Hedstrom, J. (2016) *B2B, B2B2C and startups need 3D printing services*, *Sculpteo*. Available at: <https://www.sculpteo.com/blog/2016/04/27/how-3d-printing-services-help-b2b-b2b2c-and-startups/> (Accessed: 24 July 2017).

Heinonen, K., Strandvik, T., Mickelsson, K., Edvardsson, B., Sundström, E. and Andersson, P. (2010) 'A customer-dominant logic of service', *Journal of Service Management*, 21(4), pp. 531–548. doi: 10.1108/09564231011066088.

Henning, J. (2013) *Is the Ideal Survey Length 20 Minutes?*, *Research Access*. Available at: <http://researchaccess.com/2013/12/survey-length/> (Accessed: 26 November 2017).

Holland, S., Foster, T., MacNaughtan, W. and Tuck, C. (2016) 'Design and characterisation of food grade powders and inks for microstructure control using 3D printing', *Journal of Food Engineering*. Elsevier Ltd, pp. 4–11. doi: 10.1016/j.jfoodeng.2017.06.008.

IDEO (2009) *Design Kit: The Human-Centered Design Toolkit*, *IDEO.org*. Available at: <http://www.designkit.org/> (Accessed: 12 June 2017).

Izdebska, J. and Zolek-Tryznowska, Z. (2016) '3D food printing - Facts and future', *Agro Food Industry Hi-Tech*.

Jiang, R., Kleer, R. and Piller, F. T. (2017) 'Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030', *Technological Forecasting and Social Change*. The Authors, 117, pp. 84–97. doi: 10.1016/j.techfore.2017.01.006.

Kaplinsky, R. and Morris, M. (2000) *A Handbook for Value Chain Research*, *International Development Research Centre*. doi: 10.1057/9781137373755.0007.

Karlgaard, R. (2011) *3D Printing Will Revive American Manufacturing*, *Forbes*. Available at: <https://www.forbes.com/sites/richkarlgaard/2011/06/23/3d-printing-will-revive-american-manufacturing/#619d20e12548> (Accessed: 29 May 2017).

Kotler, P. (1986) 'The Prosumer Movement : A New Challenge For Marketers', *Advances in Consumer Research*, 13, pp. 510–513. Available at: <http://www.acrwebsite.org/search/view-conference-proceedings.aspx?Id=6542> (Accessed: 15 August 2017).

Krader, K. (2017) 'Meet Sally, the Robot Who Makes Perfect Salads - Bloomberg', *Bloomberg Pursuits*, April. Available at: <https://www.bloomberg.com/news/articles/2017-04-04/meet-sally-the-robot-who-makes-perfect-salads> (Accessed: 3 November 2017).

Kytannen, J. (2005) 'Rapid Manufacture for the Retail Industry', in *Rapid Manufacturing*.



John Wiley & Sons, Ltd, pp. 275–282. doi: 10.1002/0470033991.ch18.

Lille, M., Nurmela, A., Nordlund, E., Metsä-Kortelainen, S. and Sozer, N. (2017) ‘Applicability of protein and fiber-rich food materials in extrusion-based 3D printing’, *Journal of Food Engineering*. Elsevier Ltd. doi: 10.1016/j.jfoodeng.2017.04.034.

Lin, C. (2015) ‘3D Food Printing: A Taste of the Future’, *Journal of Food Science Education*, 14(3), pp. 86–87. doi: 10.1111/1541-4329.12061.

Van Der Linden, D. (2015) ‘3D Food printing: Creating shapes and textures’, *Tno*, (March), pp. 1–36.

Lipton, J., Arnold, D., Nigl, F., Lopez, N., Cohen, D., Norén, N. and Lipson, H. (2010) ‘Multi-Material Food Printing With Complex Internal Structure Suitable For Conventional Post-Processing’.

Lusch, R. F., Vargo, S. L. and Wessels, G. (2008) ‘Toward a conceptual foundation for service science: Contributions from service-dominant logic’, *IBM Systems Journal*, 47(1), pp. 5–14. doi: 10.1147/sj.471.0005.

*Magic Candy Factory* (2015). Available at: <http://magiccandyfactory.com/> (Accessed: 21 November 2017).

MarketsandMarkets (2017) *Service Robotics Market by Operating Environment (Aerial, Ground, Marine), Application (Professional, Personal), and Geography (North America, Europe, Asia-Pacific, and Row) - Global Forecast to 2022*. Available at: <http://www.marketsandmarkets.com/Market-Reports/service-robotics-market-681.html> (Accessed: 3 November 2017).

Millen, C. I. (2012) ‘The Development of a Colour 3D Food Printing System’, (*Unpublished masters dissertation*).

Molitch-Hou, M. (2015) *Hershey & 3D Systems unveil new cutting-edge chocolate 3d printer at CES, 3D Printing Industry*. Available at: <https://3dprintingindustry.com/news/hershey-3d-systems-unveil-new-cutting-edge-chocolate-3d-printer-ces-39279/> (Accessed: 16 June 2017).

Mueller, B. (2012) ‘Additive Manufacturing Technologies – Rapid Prototyping to Direct Digital Manufacturing’, *Assembly Automation*. Emerald, 32(2). doi: 10.1108/aa.2012.03332baa.010.

Natural Machines (2013) *Foodini*. Available at: <https://www.naturalmachines.com/> (Accessed: 24 November 2017).

Nessler, D. (2016) *How to apply a design thinking, HCD, UX or any creative process from scratch, Medium*. Available at: <https://medium.com/digital-experience-design/how-to-apply-a-design-thinking-hcd-ux-or-any-creative-process-from-scratch-b8786efbf812> (Accessed: 24 November 2017).

NuFood (2015) *Food Robot*. Available at: <http://www.nufood.io/> (Accessed: 24 November 2017).

- Performance (2015) *Development of Personalised Food using Rapid Manufacturing for the Nutrition of elderly Consumers*. Available at: <http://www.performance-fp7.eu/project-overview/> (Accessed: 22 May 2017).
- Periard, D., Schaal, N., Schaal, M., Malone, E. and Lipson, H. (2007) 'Printing Food', *Proceedings of the 18th Solid Freeform Fabrication Symposium*, pp. 564–574. doi: 10.1007/s00216-007-1293-0.
- Persistence Market Research (2016) *3D Food Printing Market: Global Industry Analysis and Forecast 2016 - 2026*. Available at: <http://www.persistencemarketresearch.com/market-research/3d-food-printing-market.asp> (Accessed: 20 June 2017).
- Pinna, C., Ramundo, L., Sisca, F. G., Angioletti, C. M., Taisch, M. and Terzi, S. (2016) 'Additive Manufacturing applications within Food industry : an actual overview and future opportunities', *XXI Summer School Francesco Turco - Industry 4.0 Creating New Waves*.
- Poel, B. Van De (2016) 'Tomorrow's Meatball: A visual exploration of future food', *Space10: A future-living lab*. Available at: <https://space10.io/journal/tomorrow-s-meatball-a-visual-exploration-of-future-food> (Accessed: 15 June 2017).
- Poutanen, K., Emilia, N., Jaakko, P., Kaisa, V. and Åkerman, M. (2017) 'Food Economy 4.0. VTT's vision of an era of smart consumer-centric food production', *VTT Technical Research Centre of Finland Ltd*.
- Prahalad, C. K. and Ramaswamy, V. (2004) 'Co-creating unique value with customers', *32(3)*, pp. 4–9.
- Prisco, J. (2014) 'Foodini' machine lets you print edible burgers, pizza - CNN, CNN. Available at: <http://edition.cnn.com/2014/11/06/tech/innovation/foodini-machine-print-food/index.html> (Accessed: 24 November 2017).
- Rayna, T. and Striukova, L. (2016) 'From rapid prototyping to home fabrication: How 3D printing is changing business model innovation', *Technological Forecasting and Social Change*. Elsevier B.V., 102, pp. 214–224. doi: 10.1016/j.techfore.2015.07.023.
- Rayna, T., Striukova, L. and Darlington, J. (2015) 'Co-creation and user innovation: The role of online 3D printing platforms', *Journal of Engineering and Technology Management*. doi: 10.1016/j.jengtecman.2015.07.002.
- Ritzer, G., Dean, P. and Jurgenson, N. (2012) 'The Coming of Age of the Prosumer'. doi: 10.1177/0002764211429368.
- Ritzer, G. and Jurgenson, N. (2010) 'Production, Consumption, Prosumption: The nature of capitalism in the age of the digital "prosumer"', *Journal of Consumer Culture*, 10(1), pp. 13–36. doi: 10.1177/1469540509354673.
- Sharon, T. . and Zandbergen, D. (2016) 'From data fetishism to quantifying selves: Self-tracking practices and the other values of data', *New Media & Society*. Available at: [https://cris.maastrichtuniversity.nl/portal/en/publications/from-data-fetishism-to-quantifying-selves-selftracking-practices-and-the-other-values-of-data\(bfde24b9-280f-](https://cris.maastrichtuniversity.nl/portal/en/publications/from-data-fetishism-to-quantifying-selves-selftracking-practices-and-the-other-values-of-data(bfde24b9-280f-)

4700-ba49-908733db9ca6).html.

Sincero, S. M. (2012) *Online Surveys - Pros and cons of web-based questionnaires*, *Explorable.com*. Available at: <https://explorable.com/online-surveys> (Accessed: 26 November 2017).

Smith, B. (2013) *Tomorrow's Food, Today: 3 Opportunities for Disruption of the Food System*, *Wired*. Available at: <https://www.wired.com/insights/2013/09/tomorrows-food-today-3-opportunities-for-disruption-of-the-food-system/> (Accessed: 20 June 2017).

Soares, S. (2011) 'Insects Au Gratin / Project'. Available at: <http://www.susanasoares.com/index.php?id=82> (Accessed: 15 November 2017).

*Star Trek Replicator* (1987) *Star Trek*. Available at: [http://www.startrek.com/database\\_article/replicator](http://www.startrek.com/database_article/replicator) (Accessed: 22 November 2017).

Stewart-Knox, B. and Mitchell, P. (2003) 'What separates the winners from the losers in new food product development?', *Trends in Food Science & Technology*, 14(1–2), pp. 58–64. doi: 10.1016/S0924-2244(02)00239-X.

Sullivan and Frost (2015) 'Industrial Bioprocessing Alert: 3D Food Printing', *TechVision*.

Sun, J., Peng, Z., Yan, L., Fuh, J. and Hong, G. S. (2015) '3D food printing—An innovative way of mass customization in food fabrication', *International Journal of Bioprinting*. doi: 10.18063/IJB.2015.01.006.

Sun, J., Peng, Z., Zhou, W., Fuh, J. Y. H., Hong, G. S. and Chiu, A. (2015) 'A Review on 3D Printing for Customized Food Fabrication', *Procedia Manufacturing*. Elsevier B.V., 1, pp. 308–319. doi: 10.1016/j.promfg.2015.09.057.

Sun, J., Zhou, W., Huang, D., Fuh, J. Y. H. and Hong, G. S. (2015) 'An Overview of 3D Printing Technologies for Food Fabrication', *Food and Bioprocess Technology*, 8(8), pp. 1605–1615. doi: 10.1007/s11947-015-1528-6.

Tague, N. R. (2004) *The Quality Toolbox*, *ASQ Quality Press*.

Tanaka, H., Asano, Y., Watanabe, M. and Masumori, A. (2015) 'Food Printing technologies out of white rice', *International Conference on Digital Printing Technologies*, 2015–Janua, pp. 289–292. Available at: <http://www.scopus.com/inward/record.url?eid=2-s2.0-84952941349&partnerID=tZOtx3y1>.

Tapscott, D. and Williams, A. D. (2006) *Wikinomics: How Mass Collaboration Changes Everything*. New York: Penguin Books.

Toffler, A. (1981) *The third wave*.

Tran, J. L. (2016) '3D-Printed Food', *Minnesota Journal of Law, Science & Technology*, 17(2), pp. 857–879. Available at: <http://scholarship.law.umn.edu/mjlst/vol17/iss2/7>.

USDE (2014) 'Differences between qualitative and quantitative research methods', *Oak Ridge Institute for Science and Education*.

- Wegrzyn, T. F., Golding, M. and Archer, R. H. (2012) 'Food Layered Manufacture: A new process for constructing solid foods', *Trends in Food Science and Technology*. Elsevier Ltd, 27(2), pp. 66–72. doi: 10.1016/j.tifs.2012.04.006.
- Wei, J. and Cheok, A. D. (2012) 'Foodie: Play with your food promote interaction and fun with edible interface', *IEEE Transactions on Consumer Electronics*, 58(2), pp. 178–183. doi: 10.1109/TCE.2012.6227410.
- Weller, C., Kleer, R. and Piller, F. T. (2015) 'Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited', *International Journal of Production Economics*. Elsevier, 164, pp. 43–56. doi: 10.1016/j.ijpe.2015.02.020.
- Widjaja, W. and Takahashi, M. (2016) 'Distributed interface for group affinity-diagram brainstorming', *Concurrent Engineering*. SAGE Publications Ltd STM, 24(4), pp. 344–358. doi: 10.1177/1063293X16657860.
- Wisdom, J. and Creswell, J. W. (2013) 'Mixed Methods: Integrating Quantitative and Qualitative Data Collection and Analysis While Studying Patient-Centered Medical Home Models', *Agency for Healthcare Research and Quality*. Available at: <https://pcmh.ahrq.gov/page/mixed-methods-integrating-quantitative-and-qualitative-data-collection-and-analysis-while> (Accessed: 25 November 2017).
- Yang, J., Wu, L. and Liu, J. (2001) 'Rapid prototyping and fabrication method for 3-D food objects', *US. Patent*. doi: US6280785 B1.
- Zoran, A. and Coelho, M. (2011) 'Cornucopia : The Concept of Digital Gastronomy', *Leonardo, The MIT Press*, 44(5), pp. 425–431. doi: 10.1162/LEON\_a\_00243.

## **Appendix**

Appendix 1. Interview framework. 2 pages.

Appendix 2. Survey framework. 7 pages.

Appendix 3. Workshop framework. 3 pages.

Appendix 4. Posters for 3 use-cases. 3 pages.

Appendix 5. Selected quotations from interviews. 3 pages.

## **Appendix 1. Interview framework**

**Duration: 30 minutes to 45 minutes**

### **Warm-up & introduction**

- Introducing myself and the research – very briefly.
- Please tell about your education/ research background.
- Company/ project background.
- What is your general opinion about 3d printing of food?
  - What comes to your mind first when you think about it?

### **3d food printing (general)**

- What in your opinion would be the biggest value of 3d food printing?
  - For consumers?
  - For food industry/ other businesses?
- What in your opinion is the single biggest challenge in 3d food printing? Why?
  - With regards to technology feasibility.
  - With regards to economic viability.
  - With regards to consumer desirability.
- Do you see a potential in the 3d food printing technology for disrupting the food value chain? How would it help in doing so?
- Which is the most suitable technology for 3d food printing? Why?
- How important is pre-processing & post-processing in case of 3d food printing? Do you see a value in integrating a cooking or processing system to 3d food printer?

### **Future of food**

- What are the key trends and uncertainties in our food system?
- Other than the technology push, what are the factors that might impact the food industries?
  - Does it complement technology innovations like 3d food printing? How?
- In your opinion, which is the food ingredient of the future?

### **ICT innovation & rise of prosumers**

- What is your take on the emerging online platforms and its role in allowing consumers to be a part of the production process (Prosumers)?
- Do you think that the ICT developments and tech-innovations like 3d printing allow consumers to take part in the value creation process with ease? Or are there still some limitations?
- What are the characteristics of an ideal prosumer platform?
- What is the most important parameter for food customization in your opinion?
  - What does the prosumer want to customize in food?

### **Wrap-up**

- How would you envision the future of food production? Does 3d food printing play a role in it?
- Most probable scenario for 3d food printing in 2025?
- Are you willing to answer a survey that I will be preparing to finalize the collected data?

## Appendix 2. Survey framework



### 3D Food Printing & Role of a Prosumer Driven Platform

**Prosumer:** Consumer who takes part in production (food production in this case) and delivery chain in one way or the other.

**Prosumer driven platform for 3d food printing:** It may be a smartphone application that allow consumers to design, produce, and order personalized food utilizing 3d food printing technology.

**This survey aims at defining the characteristics and parameters of a prosumer platform for 3d food printing, evaluating the potential of various use-cases for such platform, and identifying suitable technologies for it.**

The survey consists of **17 multiple choice questions**, and will take approximately **10 minutes** to finalize and submit the answers.

The survey is a part of a jointly-funded **TEKES** (Finnish Funding Agency for Innovation) project - 3D Surprise (Multi-layer food textures by advanced manufacturing technologies), in collaboration with **VTT Technical Research Centre of Finland, Aalto University, and Finnish industry partners.**

*Personal as well as company specific information will be anonymous - Survey results will not reveal any company specific information.*

**Researcher Name: Siddharth Jayaprakash**  
**Organization: Aalto University, Finland**  
**E-mail Address: siddharth.jayaprakash@aalto.fi**

1. Please select the country where you work in. \*

(Dropdown menu)

2. What is the primary field of your company or organization? \*

- Research, university, or education
- 3d food printer manufacturer (developers of commercial 3d food printers)
- Food ingredients producer
- Food processor
- Distributor (retailer, stores, vending machine etc.)
- Restaurant, bakery, or catering
- Service & technology provider (e.g. software, hardware, design, or product development agency)



Other, please specify:

---

3. What is your field of expertise (multiple selection possible)? \*

- Engineering
- 3d printing
- 3d food printing
- Food science
- Material science
- Computer science
- Business strategy
- Marketing
- Innovation management
- Industrial management
- Design
- Future of food
- Sustainability
- Prosumption or prosumerism

Other, please specify:

---









Localized food production



**Thanks for the participation!**

**15.** All research outcomes will be publicly disseminated once the project is completed. If you want a personal digital copy of the outcome, please fill the form below.

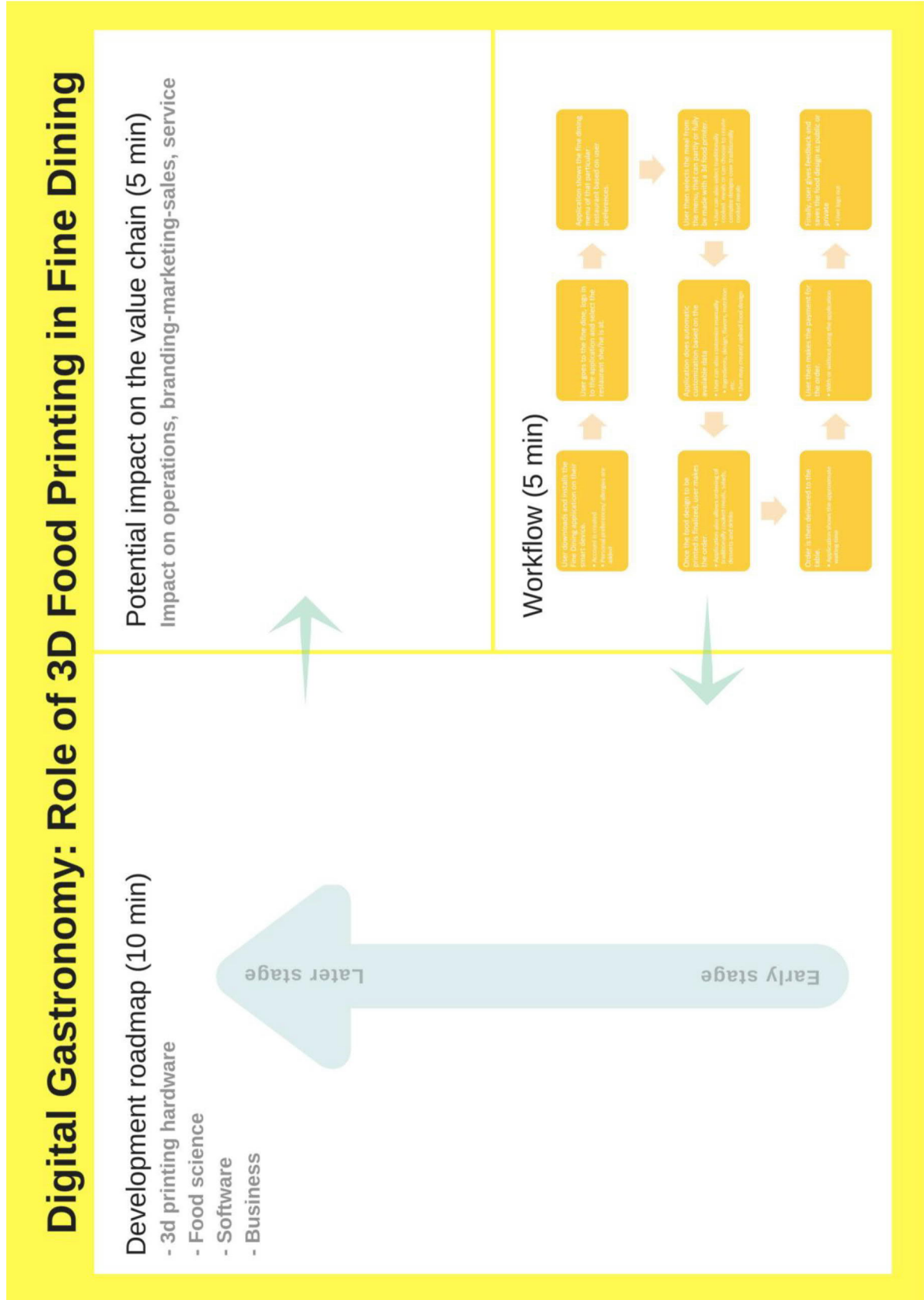
First name \_\_\_\_\_

Last name \_\_\_\_\_

Email address \_\_\_\_\_

Company / Organization \_\_\_\_\_

## Appendix 3. Workshop framework



# Personalized Snacks at Fitness Centres

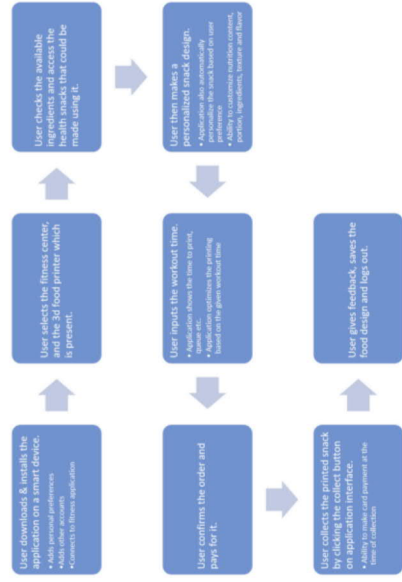
Development roadmap (10 min)

- 3d printing hardware
- Food science
- Software
- Business



Potential impact on the value chain (5 min)  
Impact on operations, branding-marketing-sales, service

Workflow (5 min)





# 3D Food Printing Vending Machines in Public Spaces

Development roadmap (10 min)

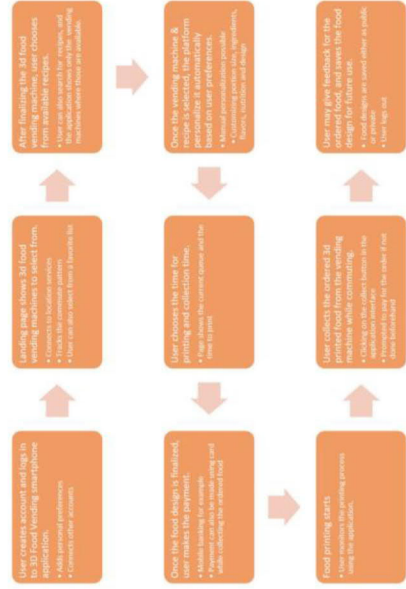
- 3d printing hardware
- Food science
- Software
- Business

Later stage

Early stage

Potential impact on the value chain (5 min)  
Impact on operations, branding-marketing-sales, service

Workflow (5 min)



## Appendix 4. Posters for 3 use-cases

# DIGITAL GASTRONOMY

Role of prosumer driven 3d food printing in fine dining

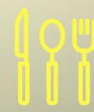
Archetype: Fine diners

Added value: Original food designs personalized for each customer, enhancing their overall eating experience

Drivers: Digital revolution, 3d food printing revolution, dynamic markets, consumer-oriented innovation



*Bringing together technology, consumer preference and a unique dining experience!*





*Combining health and personal well-being with technology and food convenience*

# PERSONALIZED SNACKS AT FITNESS CENTRES

**Added value:** Fast and easy access to personalized healthy snacks after fitness sessions



**Archetype:** Fitness enthusiasts  
**Drivers:** Convenience, personalized nutrition, digital revolution, 3d food printing revolution



*Redefining food convenience by combining public vending with prosumer driven 3d food printing*

# 3D FOOD PRINTING VENDING MACHINES IN PUBLIC SPACES

**Added value:** Easy personalization and purchase of snacks using a digital platform, same time disrupting the distribution chain



**Archetype:** Commuters, office workers  
**Drivers:** Changing eating habits, convenience, personalized nutrition, digital revolution, 3d food printing revolution



## **Appendix 5. Selected quotes from interviews**

*“User interfaces and user involvement are going to be the key drivers in the market acceptance of a technology, product, or service”*

*“Desktop 3d food printers will be worthy only if it allows automation and customization”*

*“Try not to run before you can actually walk!”*

*“Food consumers are early adopters”*

*“3d food printing isn’t going to be cheaper than conventional food production soon”*

*“Convenience is the key!”*

*“Star Trek food replicator will be a reality, and it’s just a matter of time!”*

*“3d food printing is still under-researched. Current machine concepts weren’t designed around food, but were adopted from traditional 3d printing”*

*“Food industry is driven by consumers”*

*“3d food printing helps offering a different food experience every time, even with the same ingredients”*

*“3d printed food should taste, smell, look, and feel good”*

*“It allows consumers to pull the string”*

*“Making something healthy, but that looks, feels, and tastes like its unhealthy counterparts”*

*“Value for money, consistency, and convenience are the most important attributes of a food product”*

*“Current potential of 3d food printing is limited to niche applications. Utilizing the technology in niche areas will contribute to the technology advancement for generic applications”*

*“Fine tuning of fundamentals & understanding how food materials behave in 3d printers is what that is going to happen in the coming decade”*

*“An online platform would help motivating the consumer to use the 3d food printer, and facilitates co-creation”*

*“Industry scale production will come first to the confectionery sector”*

*“We don’t want to print pizza!”*

*“Industry isn’t taking 3d food printing seriously despite its huge potential”*

*“Marketing is extremely important to showcase the potential of 3d food printing, and raise consumer awareness”*

*“Pop-ups and demonstrations at events, brings the consumers close to the technology & helps them in understanding its potential. It would also allow businesses to gain feedback and insights. In other words, it makes marketing much easier”*

*“When we think about 3d food printing, we shouldn’t limit ourselves to printing of food, but should think about the industry as a whole”*

*“3d food printing cannot compete with traditional food processing techniques in terms of price, at least now”*

*“3d food printing has a lot of potential, but capturing monetary value using it depends on finding suitable business cases”*

*“Without an innovative use-case, or a novel functional benefit, 3d food printers may end-up like the bread machines from the 1990s”*

*“The way we do business has changed significantly over the past few decades, with the arrival of internet”*

*“3d food printing by itself isn’t a very important business, but an enabler of other innovative business models”*

*“It fosters mass customization of food”*

*“Currently, 3d food printers aren’t used to its maximum potential”*

*“Early adoption is important! Take the technology to the market as fast as possible & iterate continuously”*

*“An integrated cooking system is necessary in imparting real functional value in case of 3d food printing”*

*“Real value would come once it’s possible to print personalized, nutritious food products”*

*“3d food printing is a gimmick, and the value is only in conspicuous consumption”*

*“Finding a food material that is delicious and nutritious at the same time is challenging”*

*“Grocery stores will never disappear”*

*“3d food printers won’t fit in supermarkets, but rather in public spaces”*

*“3d printed food won’t compete with traditionally produced food. It has a separate market position”*

*“A long way to go for industrial scale adoption”*

*“Involve consumers in the food innovation process”*

*“It is important to create a suitable story and align it with the brand strategy”*

*“More collaboration among industry players and researchers is required for the mutually beneficial technology advancement of 3d food printing”*

*“It is something fun & novel”*

*“It is amazing to see how technology continuously changes the world we live in”*

*“Prosumer platform will play an important role in overcoming many uncertainties related to 3d food printing”*

*“What is the added value for 3d printing food?”*

*“After seeing the outcome of Barilla pasta printer, many food brands started taking 3d food printing seriously”*