Business model patterns in the 3D food printing industry

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Abstract

Purpose – Present for more than 20 years, 3D food printing (3DFP) technology has not experienced the same widespread adoption as its non-food counterparts. It is believed that relevant business models are crucial for its expansion. The purpose of this study is to identify the dominant prototypical business models and patterns in the 3DFP industry. The knowledge gained could be used to provide directions for business model innovation in this industry.

Design/methodology/approach – The authors established a business model framework and used it to analyse the identified 3DFP manufacturers. The authors qualitatively identified the market's prototypical business models and used agglomerative hierarchical clustering to extract further patterns.

Findings – All identified 3DFP businesses use the prototypical business model of selling ownership of physical assets, with some variations. Low-cost 3D food printers for private usage and dedicated 3D food printers for small-scale food producers are the two primary patterns identified. Furthermore, several benefits of 3DFP technology are not being used, and the identified manufacturers are barely present in high-revenue markets, which prevents them from driving technological innovation forward.

Practical implications – The extracted patterns can be used by the companies within the 3DFP industry and even in other additive manufacturing segments to reflect upon, refine or renew their business model. Some directions for business model innovation in this industry are provided.

Originality/value – To the best of the authors' knowledge, this is the first quantitative study to give an account of the current 3DFP business models and their possible evolution. This study also contributes to the business model patterns methodological development.

Keywords 3D food printing, 3DFP, Additive manufacturing, Business model patterns

Paper type Research paper

1. Introduction

3D food printing (3DFP) is the application of additive manufacturing (AM) techniques in food processing. This technology was first described in a patent in 2001 by Nanotek Instruments (Yang *et al.*, 2001), and the first functioning printers capable of creating 3D objects from food material reached the market in 2006 (Malone and Lipson, 2007; Sher and Tutó, 2015). The unique ability to produce highly complex shapes with little or no extra effort offers the possibility of creating edible printed material with extraordinary designs

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(Mantihal *et al.*, 2020). Other benefits, such as the production of more appealing food for the elderly in hospitals (Chua *et al.*, 2018; Lipton *et al.*, 2015), personalised meals based on modified and tailored nutrition, texture and consistency, have also been explored (Sun *et al.*, 2015; Yang *et al.*, 2017; Mantihal *et al.*, 2020; Burke-Shyne *et al.*, 2021). However, while 3D printing has been widely adopted for industrial-scale production in many industries, the application of large-scale 3DFP remains an unrealised potential (Le-Bail *et al.*, 2020; Mantihal *et al.*, 2020), the technology being mainly available to individual users for recreational purposes and to small-scale food production businesses, such as restaurants, confectionery and pastry shops (Mantihal *et al.*, 2020). In addition to the technological barriers (Burke-Shyne *et al.*, 2021; Wendin *et al.*, 2010) and consumers' unfamiliarity with food produced using such methods (Cardello *et al.*, 2007), companies wishing to successfully innovate and make a profit from this technology are also faced with a high degree of uncertainty as to whether the technology will create sufficient customer value and become an economically viable method of food production (Sun *et al.*, 2018; Mantihal *et al.*, 2020).

One way to analyse and understand how value is created, delivered and captured in the 3DFP industry, as well as how these activities can subsequently be improved at the company level, is to study its business model patterns (Remane *et al.*, 2017). Business model patterns are groupings of "business models with similar characteristics, similar arrangements of business model Building Blocks, or similar behaviors" (Osterwalder and Pigneur, 2010, p. 55; see also Remane *et al.*, 2017, for further definitions). Business models, in turn, define how the enterprise creates and delivers value to customers and then converts payments received to profits (Teece, 2010); it provides a view of relationships between the product, the customer and the company selling the product; business models also impact technological innovation as profitable business models encourage further innovation of hardware and software technologies (Godoi *et al.*, 2019). While the importance of business model patterns to support industrial development is well-recognized (Osterwalder and Pigneur, 2010; Gassmann *et al.*, 2014; Amshoff *et al.*, 2015; Remane *et al.*, 2017), research interest in business models in the 3DFP industry has been very limited (Rayna *et al.*, 2015; Ramundo *et al.*, 2020). The purpose of this paper is to review the business models implemented by current 3DFP manufacturers to identify the business model patterns in the 3DFP industry. The business models patterns will give a better understanding of the current attempts at the commercialisation of 3DFP technology; the knowledge gained could also be used to provide directions for business model innovation (Bashir *et al.*, 2020) regarding both current 3DFP technology and the next generation of 3D-printed food and food printers.

The remainder of this paper is organised as follows: the background of 3DFP and previous studies on business models and business model patterns within 3DFP are provided in Section 2. The business model pattern analysis methodology, including the identification of 3DFP companies, is described in Section 3. The results are presented in Section 4 and are discussed in Section 5. Finally, Section 6 concludes the study.

2. Background and theory

2.1 The development of the 3D food printing industry

Although the intention of using AM technology for food was recognised early on (Yang *et al.*, 2001), what attracted early interest in using edible materials for 3D printing was its easy accessibility, relatively low cost as printing material and biodegradability (Periard *et al.*, 2007), but not necessarily as something meant to be eaten (Malone and Lipson, 2007). Examples in this category include the Fab@Home series of cost-effective 3D printers (Lipton *et al.*, 2011) and CandyFab sugar printers (Wegrzyn *et al.*, 2012), which were primarily intended to increase access to 3D printing technology by lowering the cost of printing material.

Mainly, since around 2010, 3DFP systems have been commercialized for consumption (see e.g. Dankar *et al.*, 2018; Wegrzyn *et al.*, 2012). Examples of commercialized 3D printed food include chocolate gifts (Jia *et al.*, 2016), fancy sugar cubes and pasta (Sher and Tutó, 2015).

On the research front, several projects are oriented towards the possibilities to create new food perceptions by altering food structure (Derossi *et al.*, 2021) or appearance (Lin *et al.*, 2020). The use of 3D printers to produce easy-to-swallow food for the elderly suffering from dysphagia has attracted much interest (Chua *et al.*, 2018; Lipton *et al.*, 2015). With its ability to precisely place a controlled amount of ingredients within food, 3D printers can potentially be used to produce personalised meals based on consumer-specific data to better govern their diet (Lipton, 2017). 3DFP has also been explored for its potential to improve the quality of food for astronauts in space missions (Jiang *et al.*, 2020) and to create better drug-release characteristics in pharmaceutical applications (Dumitrescu *et al.*, 2018).

2.2 Adopted perspective on business models and business model patterns

Several views of business models and business model patterns exist. This section describes the perspective adopted for this study. A business model is necessary to discover a path to the market, enabling a technological innovation to deliver value to the customer (Chesbrough and Rosenbloom, 2002). According to Abdelkafi *et al.* (2013), "a business model describes how the company communicates, creates, delivers, and captures value out of a value proposition". Business models can be used as analytical tools to understand how firms adapt to new technological challenges (Baden-Fuller and Mangematin, 2013). By describing them with their business models, companies' unique and complex processes of creating, communicating, delivering and capturing value from their value proposition can be understood and compared. A business model can be broken down into components such as value proposition, value creation and value capture (Osterwalder and Pigneur, 2010; Günzel and Holm, 2013), each of these components representing the key activities performed by the organisation. The activities or combinations of activities observed across several organisations form business model patterns that can potentially be applied to other businesses and are expected to deliver similar effects (Remane *et al.*, 2017). One distinguishes mainly between so-called prototypical business models that holistically describe industry-specific business models and business model solution patterns (solution patterns for short) that are reoccurring combinations of business model elements (Amshoff *et al.*, 2015). Several prototypical business models and solution patterns have been gathered from different industries, see e.g. (Abdelkafi *et al.*, 2013; Malone *et al.*, 2006; Amshoff *et al.*, 2015; Gassmann *et al.*, 2014; Remane *et al.*, 2017).

2.3 Business models and business model patterns in the 3D food printing industry

Although the connection between AM technology and its business model has attracted the attention of researchers (Bogers *et al.*, 2016; Savolainen and Collan, 2020; Holzmann *et al.*, 2020), studies on business models for 3DFP are scarce (Ramundo *et al.*, 2020). Only two studies could be found. In one, Flammini *et al.* (2017) discuss business model innovation as a possibility to face uncertainties of entering a mature and conservative market such as the food industry, illustrated by the case of a company that started to exploit 3DFP. In the other, Jia *et al.* (2016) investigated the business models of different actors involved in the value chain of a 3D chocolate printing technology. The study shows that 3D chocolate printing has the potential to generate value for technology adopters and change the relationships between players within the supply chain. These early studies illustrate the role business models can have on the 3DFP industry.

Regarding business model patterns in 3DFP, no study was found. Holzmann *et al.* (2019) were the only one who investigated business model patterns in the AM industry, but it did not include 3DFP companies, as noted by Rayna *et al.* (2015). Holzmann *et al.* (2019) found two main patterns in AM, which can have a bearing on the present study: the "low-cost online business model" (with the general value proposition of providing quality printers at low cost) and the "technology expert business model" (with focus on expertise, innovation leadership and quality). However, the business models that are successfully used with non-food 3D printing technology are not necessarily compatible with the technology for food production, one reason being that 3DFP possesses some unique challenges, including food formulations development, transport and storage, hygienic requirements and sensory attributes experienced by the consumer (Dankar *et al.*, 2018; Wendin *et al.*, 2010; Burke-Shyne *et al.*, 2021). It is, therefore, highly relevant to investigate specifically the business model patterns of the 3DFP industry.

3. Methodology

The implemented methodology is an adaptation of Amshoff *et al.* (2015)'s general methodology. The methodology has been used in previous studies, e.g. Curtis (2021) and Pieroni *et al.* (2021). It comprises four steps. Firstly, the relevant 3DFP manufacturers are identified. Secondly, a business model framework is established. A business model framework consists of a set of business model elements, generic or specific to the studied industry. These business model elements are used to characterise the business models of the identified companies. This characterisation takes the form of a "binary characteristic list", as described further below. Thirdly, this binary characteristic list is used to identify and describe the industry's prototypical business models. Finally, the solution patterns are extracted from the binary characteristic list. These four steps are described in detail below.

3.1 Identification of 3D food printing manufacturers

In this step, 3D food printer models and their manufacturers were identified by scanning academic publications, industry reports and product reviews on the internet. The search started on Google Scholar with keywords including "3D food printing", "3D printed food" and combinations of "Additive manufacturing", "3D printing" and "Food". The snowball technique (Jalali and Wohlin, 2012) was used to further identify relevant publications. This process was continued until no new information was obtained. Further searches on the internet, discussion forums and commercial product reviews also yielded more 3D food printers that were not mentioned in the literature. In principle, many 3D printers can be configured to print with food materials, and many companies market their products as multifunctional printers capable of printing various materials, including food. To maintain a focus on 3D food printers, companies that did not specifically market their 3D printers for food printing were excluded. Finally, we verified whether the identified 3D food printers were commercialised. Only those products that were available at the time of study or had been available on the market were considered commercialised. The data collection was completed in February 2022.

The authors identified 38 companies and organisations that have developed or produced one or more 3D food printer models. Of these 38 manufacturers, 22 have effectively commercialised their printers. Two early 3D food printers have discontinued commercial operations, but their business-related information is still accessible and, as a result, they have been included in a total of 24 manufacturers. Except for two manufacturers, the 3D food printer models of the companies investigated in this study are based on a single food printing technology.

3.2 Establishment of a business model framework and binary characteristic list

The structure used for the establishment of the business model framework in this study follows (Amshoff *et al.*, 2015), also applied by Curtis (2021) and Tangour *et al.* (2019). This structure is constituted of *components*, which are decomposed into *variables*, each variable itself further decomposed into *configuration options*. The components are generic business model elements that are industry-independent. The variables are attributes that characterise different aspects of a component. The configuration options describe different business practices; these are alternatives available to each variable (Curtis, 2021; Amshoff *et al.*, 2015). For example, press release, website and social media are possible configuration options for the variable *channels for communicating values* which, itself, is an attribute of the component *value communication*.

At the component level of the framework, we adopted the five components proposed by Abdelkafi *et al.* (2013): *value proposition*, *value creation*, *value communication*, *value delivery* and *value capture*. The variables were identified from previous studies on business model patterns in general, e.g. Osterwalder and Pigneur (2010) and Remane *et al.* (2017) and AM in particular, e.g. (Holzmann *et al.*, 2019). The configuration options were identified:

- **from the business model studies with the AM industry, e.g.** Holzmann *et al.* (2019); and
- **from the 3DFP literature, e.g.** Godoi *et al.* (2016), Mantihal *et al.* (2020) and Wegrzyn *et al.* (2012).

The obtained business model variables and their sources are described below. The full business model framework is shown in Table 1.

Within this framework, the *value proposition* component represents the company's bundle of products and services (Osterwalder and Pigneur, 2010). Three business model variables that differentiate different types of 3D food printers were identified: *deposition technique* (Godoi *et al.*, 2016), *print material type* and *source of materials* (Wegrzyn *et al.*, 2012). The *value creation* component describes a company's resources, knowledge, and how they are transformed into a value proposition (Abdelkafi *et al.*, 2013). Three *value creation* variables were identified, two of which were unique to 3DFP. Firstly, the *intended values* are the direct benefits expected to be obtained from the 3D-printed food (Mantihal *et al.*, 2020). The second variable identified is the *development path* of 3D food printers which reflects the different nature of 3D food printers as they progress from being an application of non-food 3D printing technology into a class of their own. The third variable, *key partnerships*, is also often associated with the *value creation* component (Abdelkafi *et al.*, 2013; Osterwalder and Pigneur, 2010) and was, therefore, included. The information about channels for interacting with customers is covered in the *value communication* component (Abdelkafi *et al.*, 2013). For this component, only one variable was identified: *channels for communicating value* (Osterwalder and Pigneur, 2010). The *value delivery* component is used to describe the targeted customer segment and how the value proposition is passed on (Abdelkafi *et al.*, 2013; Amshoff *et al.*, 2015; Osterwalder and Pigneur, 2010). In this study, the *value delivery* component comprises the variables *customer segments and relationships* and *distribution channels* (Abdelkafi *et al.*, 2013; Osterwalder and Pigneur, 2010). Finally, after the value proposition is delivered to the customer, the *value capture* component describes how the revenue is generated (Abdelkafi *et al.*, 2013). For this component, a *revenue stream* variable

Table 1. Business model components, variables, configuration options for 3D food printer manufacturers and an excerpt of the present study's binary characteristic list

Business model component	Variable no.	Business model variable	Description/Clarification and main sources	Configuration code	Configuration option	Configuration option no.	Company I	Company J	Company K
Value proposition	1	Deposition technique	3D printing techniques applied to food processing (Godoi *et al.*, 2016)	A	Soft-materials extrusion	1A	1	1	1
				B	Melting extrusion	1B	1	0	0
				C	Hydrogel-forming extrusion	1C	0	0	0
				D	Material jetting	1D	0	0	0
				E	Binder jetting	1E	0	0	0
				F	Selective laser sintering	1F	0	0	0
				G	Hot air sintering and melting	1G	0	0	0
	2	Print material type	Types of the raw food material used for printing (Wegrzyn *et al.*, 2012)	A	Food paste	2A	1	1	1
				B	Powder/Granular	2B	0	0	0
				C	Solid/Pallet	2C	0	0	0
	3	Source of material	Origin of the food material bought in or prepared in-house (Wegrzyn *et al.*, 2012)	A	Pre-packaged ingredients	3A	0	0	0
				B	Consumer-chosen/ Prepared ingredients	3B	1	1	1
Value creation	4	Development path	4A and 4B reflect the different natures of 3D food printers as they progress from being an application of non-food 3D printing technology into a class of their own (Authors)	A	Non-food printer that can print with food material	4A	0	0	0
				B	Dedicated food printer	4B	1	1	1
	5	Intended value	Type of direct benefit expected from 3D-printed food (Mantihal *et al.*, 2020)	A	Creative design	5A	1	1	1
				B	Personalized nutrition	5B	0	0	0
				C	Unique product texture	5C	0	0	0

(continued)

Business model component	Variable no.	Business model variable	Description/Clarification and main sources	Configuration code	Configuration option	Configuration option no.	Company I	Company J	Company K
	6	Key partnership	External co-operations used during the creation of value (Holzmann, 2019; Osterwalder and Pigneur, 2010)	A	Academic partners	6A	0	1	0
				B	Company partners	6B	1	1	0
				C	Customer partners	6C	0	0	0
Value communication	7	Channel for communicating value	Only the main identified types of channels have been chosen as configuration options (Holzmann, 2019; Osterwalder and Pigneur, 2010)	A	Press releases	7A	1	0	1
				B	Social media	7B	1	1	1
				C	Web page	7C	1	1	1
Value delivery	8	Customer segment and relationships	Targeted customer (Lipton *et al.*, 2015)	A	Consumer-produced foods	8A	0	0	0
				B	Small-scale food production	8B	1	1	0
				C	Industrial-scale food production	8C	0	0	1
	9	Distribution channel	How the 3D food printer is distributed (Remane *et al.*, 2017)	A	Retail shop	9A	0	0	0
				B	Webshop	9B	1	1	1
				C	Reseller/Distributor	9C	0	0	0
Value capture	10	Revenue stream	Sources from which revenue is generated (Osterwalder and Pigneur, 2010)	A	Asset sale	10A	1	1	1
				B	Reselling consumables	10B	1	1	0
				C	Rental	10C	0	0	0
				D	Leasing	10D	0	0	1

Table 1.

with four revenue source configuration options is used. These configuration options include asset selling, reselling consumables, rental and leasing (Holzmann *et al.*, 2019).

Each company could then be represented by a set of configuration options within the business model framework. A binary characteristic list is a record of the business model configuration options used or not by each manufacturer, with 1 indicating the presence of the characteristic in the company and 0 indicating the absence of the configuration option (Tangour *et al.*, 2019). An excerpt of the present study's binary characteristic list can be found in Table 1 is not in Section 4.

3.3 Selection of the prototypical business models

Prototypical business models were extracted with the help of the business model framework and the binary characteristic list established in the former step and by using Malone *et al.* (2006)'s approach. Malone *et al.* (2006) have proposed 16 types of prototypical business models that can be used to differentiate between companies with similar business characteristics as well as an approach to enable their selection within an industry. This approach is based on a set of key questions leading to the most relevant prototypical business models, e.g. "what is being sold?", "how much does the business transform the asset?" and "what type of asset is involved?" (Malone *et al.*, 2006). For example, a company that transforms a physical asset significantly and sells ownership of that asset for profit would be classified as an instance of the Manufacturer prototypical business model by this method. Similarly, the Wholesaler/Reseller prototypical business model is used to characterise the businesses that make a profit from the sale of physical assets with little to no modification.

3.4 Extraction of solution patterns

Extracting solution patterns amounts to grouping the configuration options that co-occur more frequently together than with others. This grouping is done through the binary characteristic list, and methods suitable for this are classification methods. Several classification methods have been used to extract business model patterns using binary variables (Amshoff *et al.*, 2015; Hunke *et al.*, 2017; Holzmann *et al.*, 2019; Curtis, 2021). For this study, the small size of the dataset precludes the use of "data-greedy" methods. The present study was, therefore, based on an agglomerative hierarchical clustering (AHC) analysis with the support of heatmap analysis, with multi-dimensional scaling (MDS) and co-occurrence network analysis, also called community detection or graph clustering (Newman, 2018; Brandes *et al.*, 2008; Borcard *et al.*, 2018) used for triangulation purposes.

Co-occurrence network analysis has not been used in relation with the extraction of solution patterns, and its benefits and limitations are highlighted in the supplementary material. The chosen proximity measure for the AHC analysis was the Sorensen-Dice index, which is an asymmetrical proximity measure that fits well with the clustering of this type of binary variables. The unweighted pair group method (UPGMA) with arithmetic mean and complete linkage methods were used to create the hierarchical clustering. The most relevant cluster partitions were extracted based on the agreement level of the following internal cluster quality indices: the agglomeration coefficient (distances at which objects/clusters are grouped), the point-biserial correlation coefficient, the McClain-Rao index, the Gamma index, the C-index and the silhouette coefficient. The Lance-Williams non-metric measure, a distance that is the complement of the Sorensen-Dice measure in the case of binary variables (Anderberg, 1973, pp. 112–113), was used to perform the MDS. The AHC and MDS analysis was performed using IBM SPSS Statistics (Version 27) using Orlov (2022)'s macros for the computation of most internal cluster quality indices. The co-occurrence network analysis was performed using R (Version 4.2.0). The detailed technical description of the AHC, MDS and co-occurrence network analysis methods is presented in the supplementary material. The raw data, SPSS input files and code are also appended for reproducibility purposes.

4. Results

This results section is organized as follows. The business model framework and its descriptive statistics, organized by business model components, are summarized in the first section. The second section presents the identified prototypical business models, and the last section the extracted solution patterns.

4.1 Business model framework

The business model framework, consisting of the five business model components proposed by Abdelkafi *et al.* (2013), was broken down into 10 variables and 34 configuration options. These variables and configuration options were established as presented in Section 3.2. The business models of the identified companies could be all described by this business model framework. Table 1 presents the full business model framework, with the sources of the variables and configuration options, as well as an excerpt of the binary characteristic list. The complete binary characteristic list is available in the supplementary material.

The binary characteristic list is summarised here by components:

- *Value proposition* component. This component indicates that the main technology used is by far extrusion using food paste (79%). Twenty-five per cent of the companies propose pre-packaged ingredients to use with their printers. Of the other available technologies, only hot air sintering and melting (1G) and binder jetting (1E) are implemented. Hydrogel-forming extrusion (1C), material jetting (1D) and selective laser sintering (1F) were not commercially available at the time of the study.
- *Value creation* component. Ninety-six per cent of the companies use the configuration option *creative design* as their main offering, only two companies target personal nutrition and none use the possibility to create unique product textures. Half of the companies have key partnerships in the form of *academic partners* (33%) and/or *industrial partners* (25%).
- *Value communication* component. Half of the companies use press releases, two-thirds use social media and almost all companies communicate their products through dedicated Web pages.
- *Value delivery* component. Fifty-eight per cent of the companies sell to consumers, 50% to small-scale food production businesses and two companies sell to businesses with industrial-scale food production (Barilla and Beehex). The distribution channels (retail shops, webshops and resellers/distributors) are all largely used by the companies, with several companies using more than one channel.
- *Value capture* component. This component, consisting of the *revenue stream* variable, shows that companies derive their income mainly from selling their printers (79%) or consumables (pre-packaged ingredients, 50%).

4.2 Prototypical business models

Using the business model classification of Malone *et al.* (2006) as an analysis tool, it can be concluded that all 24 selected 3DFP businesses fall into the Manufacturer prototypical business model or use a combination of the Manufacturer and Contractor prototypical business models. Both the Manufacturer type and the Manufacturer–Contractor type can be said to be prototypical of the 3DFP market.

4.2.1 Manufacturer prototypical business model. This is the 'pure' Manufacturer prototypical business model in which a company creates and sells physical assets in the form of 3D food printers (Malone *et al.*, 2006). The majority of companies in the group of 3D food businesses selected for this study belong to this group, with 18 using it as their sole prototypical business model. It is noticed in one company, Beehex, that a leasing offer is available along with the usual purchasing offer. This form of *value capture*, including leasing and renting, is a characteristic of the Physical landlord business model, in which a company sells the right to use a physical asset for revenue (Malone *et al.*, 2006).

4.2.2 Manufacturer–contractor prototypical business model. The Contractor business model generates revenue by selling services (Malone *et al.*, 2006). These companies use the Manufacturer business model and develop their own 3D food printers. However, they do not primarily sell these as products. Instead, 3D food printers are used as a tool to deliver various types of services. Barilla, Chocolate3, Nourished and Sugar Lab produce and sell 3D-printed food in the form of pasta, chocolate, gummy vitamins and sugar cubes, respectively. Two other companies, Dovetailed and Katjes Fassin UK, use their 3D food printers to create a unique experience for their customers.

4.3 Solution patterns

The most relevant solution patterns, according to the AHC analysis, consist of a set of eight clusters. The silhouette values of the obtained clusters are all above 0.25, with most of them around or above 0.50, which shows that the results are quite robust (Kaufman and Rousseeuw, 1990, p. 88). The MDS and co-occurrence network analyses confirm the relevance of this set. The identification of these solution patterns is presented in detail in the supplementary material. The eight clusters and their description are presented in Table 2.

5. Further analysis and discussion

The established business model framework, the selected prototypical business models and the extracted solution patterns are first analysed separately and then holistically. Possible directions for business model innovation based on the current business model patterns are then discussed.

Business model framework. Relatively few companies were identified to be engaged in this market. These companies are, in the majority, small and medium-sized companies. The binary characteristic list obtained from the business model framework shows that many companies use similar deposition techniques (mainly soft-material extrusion, 1A), print material types (food paste, 2A) and intended values (creative design, 5A). Importantly, the binary characteristic list highlights the variables and configuration options that are *not* elicited by the companies or by very few of them. For example, very few companies commercialise non-extrusion-based technologies. Likewise, the intended values of personalised nutrition (5B) and unique product texture (5C), often put forward as an advantage of 3DFP compared to classical food production systems, are hardly taken up by the current companies. Finally, revenue streams come mainly from the classical sales of assets and consumables. These elements have implications for the further development of the 3DFP market, as will be discussed later.

Prototypical business models. The study identified that the dominating prototypical business model is the Manufacturer business model, in which companies generate revenue primarily through the selling of manufactured 3D food printers, sometimes combined with the

Cluster/pattern no.	Configuration option	Pattern description
1	1A, 2A, 7C, 10A, 5A, 3B, 8A, 9C, 4A	*Low-cost, home user 3D food printer business model* The main intended value is to produce a creative design (5A) with food material prepared by users for their own consumption (8A). The printers in this category are sold mainly through resellers/distributors (9C) and are usually adapted from standard non-food (4A) extrusion 3D printers (1A), with little modification
2	7A, 7B, 3A, 9B, 10B,4B, 8B	*Dedicated 3D food printers for small-scale food producer business model* This pattern is predominantly associated with new companies and start-ups especially focused on 3DFP. These companies use 3D printers that are newly developed for printing with food materials (4B). The printers are also designed to print with special materials, which are available from the printer manufacturers (3A), becoming an additional source of revenue. Both printers and supplementary products are sold primarily through webshops (9B). Their intended customers are small-scale food producers (8B), such as restaurants or bakeries. This group of companies is noticeably more active on various social media platforms (7B)
3	8C, 10D	*Leasing business model* The leasing option (10D) for a 3D food printer is observed in only one example: Beehex's 3D cake decorator, an industrial-scale machine capable of decorating several hundreds of cookies per hour
4 5	1E, 2B, 1G 1B, 2C	*Technical solutions* The technical solution patterns 4 and 5 are a combination of deposition technique and print material type variables. These two variables are linked by technological constraints. Binder jetting (1E) and hot air melting (1G) are used with powder or granular material (2B), such as sugar powder used by Sugar Lab. Melting extrusion (1B) is most often used with solid pallets (2C) of chocolate in various models of 3D chocolate printers. The combination of soft-materials extrusion (1A) and food paste printing material (2A) is also one of the technical solution patterns, but they are grouped into Pattern 1. These technical solution patterns stand on their own because they have weaker proximity to other business model configuration options
6 7 8	6A 6B 5B	*Singleton clusters* These three clusters comprise only one business model configuration option (singleton clusters): personalised nutrition (5B), academic partner (6A) and company partner (6B). Partnerships (6A, 6B) are observed in several companies; however, they do not appear to be associated with any specific set of configuration options. Value creation through personalised nutrition (5B) is observed in only two companies and is not clearly linked to other configuration options

Table 2.
Solution patterns used by commercialized 3DFP companies

Contractor business model. Seventy-five per cent of the companies belong to the Manufacturer business model, and 25% to the Manufacturer–Contractor combination. It is noted that the Manufacturer business model users comprise early comers in the field, whereas the Manufacturer–Contractor business model users are represented by more recent players.

Solution patterns. Three general patterns, two technical patterns and three singleton clusters were identified. The type of printer marketed through the first general pattern is a low-cost printer for home users. It provides users with the ability to creatively design objects using edible materials. These printers are relatively inexpensive and easy to operate. The printing material can be prepared at home by the users. In many ways, the business model resembles that of the low-cost online pattern identified by Holzmann *et al.* (2019). In fact, early 3D food printers, such as Creative Machine Lab's Fab@home, were multi-material printers capable of printing with various paste-like materials, including food. Printing with food offers users the freedom to access relatively cheap printing materials so that the manufacturers do not have to focus on materials that they may not have expertise in. Pattern 2 primarily represents newer generations of 3D food printers designed to print exclusively with food materials. These materials both improve user experience and become another source of revenue for manufacturers. Pattern 3 is very specific and will be considered in the holistic analysis. The two technical patterns have weak proximity to other configuration options and were, therefore, not part of a larger pattern. Regarding the singleton clusters 6A and 6B, it can be concluded companies choose academic partners (6A) and company partners (6B) more or less independently from the other configuration options. Finally, although its proximity measure is relatively close to that of Pattern 2, the configuration option personalised nutrition (5B) could not either be placed into a general cluster.

When these results are considered holistically, a more detailed picture of the 3DFP landscape and its evolution emerges. A detailed investigation of the companies and the *development path* variable (4A, 4B) reveals that there has been an evolution in business model adoption. Firstly, Pattern 1 (low-cost, home user 3D food printer business model) is more associated with pioneering companies (and companies using proven technologies to develop low-cost products). Pattern 1 is only used within the pure Manufacturer business model. Pattern 2 (dedicated 3D food printers for small-scale food producer business model) is associated with newer generations of 3D food printers designed to print with pre-packaged printing materials. These materials are another source of revenue for the manufacturers, and the more reliable technologies allow for the use of the Contractor business model, which is usually more profitable to the company. Pattern 2 is, therefore, used both within the pure Manufacturer business model and the Manufacturer–Contractor business model. Finally, one company recently adopted Pattern 3 (leasing business model), BeeHex, which added a leasing option to its offering, which is typical of the Manufacturer–physical landlord business model. One recognises here the scheme of business model evolution going from product offerings towards service offerings (Neely, 2008). This scheme is found in manufacturing equipment, which includes several AM and, thus, 3DFP market segments. However, there are some nuances. Similarities with other manufacturing equipment can be found for printers that use raw materials and final products that can be transported with little sensitivity to temperature, humidity or shelf life, such as chocolate or sugar. This type of material allows for the development of higher-capacity machines, which in turn lend themselves to Manufacturer–contractor and Manufacturer–physical landlord combinations. As noted by Flammini *et al.* (2017), the use of business model combinations could help firms enter an established market. Beehex, the only manufacturer presenting a leasing option suitable for customers who might only need the 3D cake decorator for a short period of time, is such an example. Other companies have compensated for material constraints by developing specific Manufacturer–contractor offerings. For example, Dovetailed, using a printer capable of printing small liquid-based gel-like food shapes, proposes event experiences for which the printer is hired. The printed food is consumed where the printer is located.

These specificities explain the differences between the present results and Holzmann *et al.* (2019)'s study on business model patterns within the AM industry, in which 3DFP was not included. Holzmann *et al.* (2019)'s main pattern, the low-cost online business model, is similar to the low-cost, home user 3D food printer business model noted in this research, but the technology expert business model pattern is not observed in the 3DFP industry. While the 3DFP industry might, in the future, meet the conditions necessary to benefit from it, its specificities might lead to other directions where different business model patterns can materialise.

This analysis has shown the dominant practices as well as the lesser-used ones. Indirectly the study can hint at directions for further 3DFP business model innovation. Our literature review has highlighted the potential of 3DFP in advanced applications such as healthcare (Dumitrescu *et al.*, 2018; Lipton *et al.*, 2015; Derossi *et al.*, 2021), benefiting from the possibility of adjusting and personalising the nutritional intake required by the individual (Lin *et al.*, 2020; Lipton, 2017). These possibilities have only been exploited to a very limited extent; companies focus on creative design (5A) much more than on personalised nutrition (5B) and unique product texture (5C). Products developed in such markets usually generate high revenues, whereas speed in these areas might be less of a problem; this, in turn, enables further technology innovations that can spill over into the mainstream 3DFP industry. Regarding technologies, extrusion-based 3DFP is widely used but has an important limitation in terms of printing speed. Other technologies that can achieve a higher output level, such as material jetting (1D) and binder jetting (1E), have been developed by very few companies. In other words, while the development of food formulations is a bottleneck for the technological innovation of 3DFP systems, several business model aspects that could favour the expansion of the 3DFP industry have yet to be explored.

6. Conclusion and future works

6.1 Identified patterns in the 3D food printing industry and directions for business model innovation

The purpose of this paper was to identify the business model patterns in the 3DFP industry to give a better understanding of the current attempts at the commercialisation of 3DFP technology and to provide hints for companies to consider business model innovation as a tool to overcome some of the barriers the industry is currently facing. What the analysis of the business model patterns shows is that, despite a slow development, business models in 3DFP evolve relatively similar to other manufacturing equipment industries: for example, the use of 3D food printers as tools for industrial-scale food production or as a part of services is slowly emerging.

The 3DFP industry presents specific technical challenges compared to other AM technologies, mainly linked to the materials used (development of food formulations and related logistics). This study shows that companies have actually developed adapted business models to manage these constraints, especially regarding value creation, delivery and capture; however, these challenges have limited the applications of 3DFP, and they help explain why Holzmann *et al.* (2019)'s technology expert business model pattern is not observed in the 3DFP industry.

With these challenges, there is a risk that the industry would not proceed beyond small-scale applications, but this study highlights some directions that the industry can take to innovate and expand further. Regarding value propositions, technologies such as binder jetting are likely to have a larger impact on industrial-scale food production thanks to their higher output speed and scalability. Several high-revenue markets, such as healthcare and customised nutrition, can be new ways of generating income, which in turn would give companies financial muscles to drive technological innovation forward. Companies might also focus on neglected business model components, such as personalised nutrition and unique texture: such distinctive features might help the companies gain a competitive advantage (Saqib and Satar, 2021).

6.2 Practical and theoretical implications

This study presents several practical implications. At the management level, the extracted patterns can help the companies reflect on their current activities or initiate self-diagnosis on their business models. They can also be used as a canvas for existing companies desiring to renew their business models or for new companies willing to enter the market (Remane *et al.*, 2017) with reservations about the uncertainties and limitations associated with reproducing existing patterns (Holzmann *et al.*, 2019).

The study has also hinted at untapped directions for further development of the industry. The special business model variants that the 3DFP industry presents could also inspire other AM segments, specifically regarding creative offerings within the Manufacturer–contractor business models. The patterns found in this study show variations compared to (Holzmann *et al.*, 2019) that the whole AM industry could benefit from.

Beyond contributing to a better understanding of 3DFP business models, their evolution and their relation to technology innovation, this study contributes to the research on business models in the context of technological innovation. As mentioned by Holzmann *et al.* (2019, p. 1295), empirical studies in this domain are scarce, and this study's empirical results add to the existing body of knowledge showing how business models and technological innovation are interlinked.

Finally, this study contributes to the business model patterns methodological development. Few empirical studies have used business model patterns. The supplementary material contains an extensive description of the methodology that can be reused for a small number of cases or small samples. Raw data and coding are also made available for full reproducibility. The use of the AHC completed by MDS and co-occurrence network analyses for triangulation led to robust and reliable results. This study presents the first use of co-occurrence network analysis for the extraction of solution patterns. As developed in the supplementary material, co-occurrence network analysis is currently limited to confirmation. It is, however, a promising tool that could be used more prominently in the future for the selection of the most relevant patterns.

6.3 Research limitations and future works

The reader needs to be aware of the limitations of the present study. The data have only been gathered from publicly available sources, and even with our best effort, we cannot pretend to be exhaustive: some manufacturers might be missing. However, the patterns are considered robust, as the results from triangulation seem to imply. Secondly, the analysis only shows a picture of the companies at the time the data were gathered. To seize the evolution of business models at the company level, other methods would be needed, such as interviews or surveys.

While this study focused primarily on the manufacturers of 3D food printers, the business model view is indispensable for the consideration of other players within the ecosystem of 3D-printed food, such as the customers, suppliers and service providers. We suggest that future research explore intermediate users of 3D food printers and how different business models can affect interactions between stakeholders along the supply chain.

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Supplementary materials

Supplementary materials of this article can be found online.

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