Impact of 3D printing and post-processing parameters on shape, texture and microstructure of carrot appetizer cake

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Highlights

- Shape, texture and microstructure are mainly modified by baking parameters
- Filling rate can control shape (swelling and deformation) of 3D-printed cake
- Interactions between nozzle diameter and baking parameters modify texture of cake
- A predictive model is proposed to target specific texture properties

Abstract

How to process novel food with different texture properties and give more space to consumer personalization? These are the main goals of 3D printing: to enable consumers to carefully select their ingredients for healthier meals and create easily complex shapes with specific texture desired. However, only few studies deal with the impact of printing and post-processing parameters on the texture of printed foods. Using a carrot-puree-based dough as a food-ink model, we studied the impact of two printing (nozzle diameter (2.5 to 6.0 mm) and filling rate (40 to 100%)) and two post-processing (time (10 to 30 min) and temperature (120 to 220 °C) of baking) parameters. A Response Surface Design experiment (26 trials) showed the major influence of baking parameters on texture (ex.: crust strength, mean force) and microstructure (total pore area) of 3D-printed cakes. The nozzle diameter impacted their textural properties while the filling rate changed their shape.

Industrial relevance text

3D food printing has a lot of potential to offer foods with specific composition and texture. However, more information is needed about the combined influence of printing and post-processing parameters on texture of 3d-printed foods. In this study, a predictive model was established based on four parameters: nozzle diameter, filling rate, baking time and baking temperature. Statistical analysis also enables a back-engineering approach: in the range of texture of the study, knowing the desired texture, we can know the values of printing and post-processing parameters to apply to get the final product. The results of this experimental design and the use of the desirability function will be relevant tools to develop printed cakes with precise textural and microstructural characteristics desired by consumers. This first approach based on instrumental texture study gave us some good keys to continue with sensorial description, as well as visual and sensory appreciation by consumers.

Keywords : 3D food printing, post-processing, dough, food texture, desirability function, back-engineering

1. Introduction

3D printing, also known as additive manufacturing, allows making a 3D object by stacking layers of material. The object must first be drawn using a computer-aided design tool, then software organizes the cutting of the layers and sending it to the 3D printer (Brunner, Delley, & Denkel, 2018). Since the last 10 years, 3D food printing is growing and different food printing techniques have been developed: cold or hot-melt extrusion, selective laser sintering, inkjet printing and fused deposition modeling (Gholamipour-Shirazi, Kamlow, Norton, & Mills, 2020; Sun et al., 2015). 3D extrusion printing is the most widely used technique as it enables the printing of a wide variety of food products.

To achieve 3D food printing, three factors seem essential to control: printability (ability to extrude, support the weight of the next layer, and maintain the final shape), applicability (to obtain specific properties ex.: textural, nutritional, functional) and post-processing feasibility (resistance of the printed food to different drying or cooking techniques) (Godoi, Prakash, & Bhandari, 2016). Several printing parameters were studied to optimize the printability, stability and quality of various printed products. The main parameters studied for printing foods such as dough (Liu, Liang, Saeed, Lan, & Qin, 2019), gels (Wang, Zhang, Bhandari, & Yang, 2018; Fanli Yang, Zhang, Bhandari, & Liu, 2018), mashed potato (Liu, Bhandari, Prakash, & Zhang, 2018) or snack (Derossi, Caporizzi, Azzollini, & Severini, 2018) were printing speed, nozzle moving speed, nozzle diameter, layer height, filling rate and fill pattern. These studies have demonstrated the importance of knowing the rheological and mechanical properties of the products to be printed as well as the multiple adjustments necessary to optimize print quality and stability. After printing, different cooking methods have been used such as air frying or steaming (Caulier, Doets, & Noort, 2020), broiling or frying (Lipton et al., 2010), infrared cooking (Hertafeld et al., 2019), etc., but baking in an oven seems to be the most used method. In addition, some studies investigated the impact of post-printing treatments by baking, for example, printed cereal-based food (Severini, Azzollini, Albenzio, & Derossi, 2018; Severini, Derossi, & Azzollini, 2016; Zhang, Lou, & Schutyser, 2018), protein/fiber rich food (Lille, Nurmela, Nordlund, Metsä-Kortelainen, & Sozer, 2018) or cookie dough (Kim, Bae, & Park, 2018) in an oven. Their results demonstrated that the baking parameters and recipe formulation modified the shape (swelling, sagging and deformation) and that the water loss during baking modified the texture of the printed products. However, few studies have investigated the combined impact of printing and post-processing parameters on the textural properties of printed and baked foods. For example, Severini et al., (2016) showed the effects of filling rate (10 to 20 %) and layer height (0.3 to 0.5 mm) on cereal-based products after printing and baking, but using only one cooking condition at 200 °C during 15 min. In addition, the model used with low filling rate (cylinder) does not allow understanding the impact of printing parameters on more complex food product such as cake (with higher filling rate).

Considering that printing and baking parameters can modify the texture of foods and that 3D food printing aims to offer foods of various textures that meet the desires and needs of consumers, it is essential to better understanding these different parameters. The aim of this study was first to understand the individual impact of the printing (nozzle diameter and filling rate) and post-processing (baking time and temperature) parameters as well as their interactions on shape, texture and microstructure of appetizer cake using a carrot-puree-based dough as a food-ink model. Secondly, the objective was to provide a predictive model to obtain the precise printing and post-processing parameters to use according to the targeted properties.

2. Material and Methods

2.1. Ingredients

The dough was prepared with wheat flour (Type 55, Villa Bleue, Minoterie Bourseau, France), distilled water and carrot puree (Réf. 006716, Picard, France). The protein content was determined using Dumas method (N x 5.7) (NF EN ISO 16634-2, Groupe Qualtech, France) for the wheat flour and was provided by the supplier for carrot puree (Picard, France). The humidity percentage of carrot puree and wheat flour were respectively determined by weighing the dried matter after 5 h at 103 °C (Etuve EM10,Chopin Technologies, Villeneuve-la-Garenne, France) and by a reference method for cereals-based products (NF EN ISO 712, Goupe Qualtech, France). The printable recipe developed by Masbernat (2021) with 20 % of carrot puree and with a total water content of 65 % was used. Table 1 presents the composition of each ingredients and the amount used to prepare 600 g of dough.

Table 1. Composition and amount of ingredients used in each recipe to produce 600 g of carrot-puree-based dough.

Ingredients	Components (g/100g)		Amount used (g)
	Protein	Humidity	
Distilled water	0	100	250.3
Wheat flour	10.03 ± 0.01	13.8 ± 0.1	229.7
Carrot puree	0.6	90.1 ± 0.1	120

2.2. Preparation of the gelatinized printable recipe

The wheat flour was stirred using planetary mixer equipped with a leaf device (KSS45 EOB CLASSIC, KitchenAid, USA) at speed 2 during 1 min to avoid lumps. Distilled water and carrot puree at 20 ± 1 °C were added to wheat flour and stirred at speed 4 (~ 120 rpm) during 12 min. The dough was then transferred to a multifunction robot (Vorwerk, Thermomix TM6, FR) for thermomechanical treatment (85 °C, 15 min, speed 1 (100 rpm)). The temperature of the dough after treatment was over 60°C to ensure the gelatinization of the starch. The gelatinized dough was stored in the refrigerator at 4°C overnight and the next day it was put at room temperature about 1 hour before printing to obtain a dough at 20 ± 1°C which corresponds to a temperature allowing a good extrusion of the dough.

2.3. Printing and baking of carrot appetizer cakes

A prototype of 3D food printer built by Dagoma (Roubaix, France) was used in this study (Figure 1). The prototype is equipped with a plate moving on Y axis and a magnetic syringe rack moving on X and Z axes. The gelatinized dough (20 ± 1 °C) was poached in the syringe using a piping bag and an anti-reflux cap was inserted at the end of the syringe.

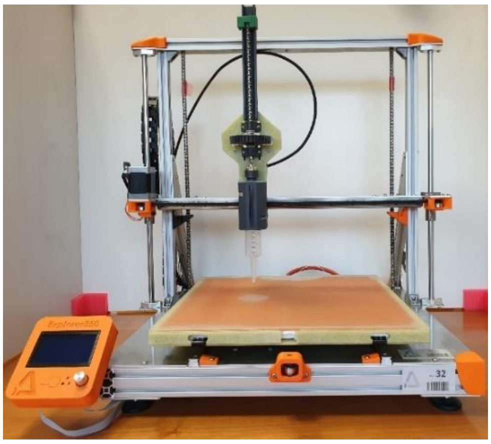


Figure 1. Prototype of 3D food printer by Dagoma

2.3.1. Preliminary tests

A preliminary study was performed to determine the printing parameters having the most impact on the texture of the printed dough. From Cura software (version 4.3.0, Ultimaker, NL), 176 printing parameters were identified and classified in 14 groups (model shape and dimension, quality, shell, infill, material, speed, displacement, cooling, supports, adhesion, double extrusion, corrections, special modes, experimental). All parameters depending on the adjustment of another parameter were removed (ex. height and width of the printing layer depending on the diameter of the nozzle used) as well as parameters not applicable to food printing (ex. supports) or to our prototype printer (ex. double extrusion). In addition, all the specific parameters aiming to improve the printing quality (ex. retraction speed) were excluded for this study since it was unlikely that these parameters modifies the texture of the printed cakes. Some parameter also had to be fixed such as the printing speed, which was fixed at 10 $mm.s^{-1}$ to allow a good print quality and adherence of our dough. Regarding the shape and dimension of the print model, a cylindrical shape (diameter: 3 cm, height: 1.5 cm) was chosen to represent appetizer cakes. Finally, the nozzle diameter and the filling rate were the most appropriate parameters for this study aimed at modifying the texture of cakes.

Preliminary tests were also carried out to target the minimum and maximum limits of the nozzle diameter and the filling rate allowing a good printing quality of the dough and respecting the dimensions of the printing model. Other preliminary tests were performed to determine the limits of baking temperature and baking time in an oven of the 3D printed appetizer cakes. The dough was printed on baking paper and baked directly after printing.

2.4. Experimental design

To predict process parameters (printing and baking) while understanding their individual impact and interactions, we performed a composite central plane allowing fitting a full quadratic model. Table 2 presents the experimental design of 26 trials to study two printing (nozzle diameter and filling rate) and two baking (temperature and time) parameters. Seven dependent variables (*Y*) were analysed: crust strength (N), mean force inside cake (N), gradient after crust penetration (N/s), maximum height (mm), maximum width (mm), mass loss (%) and total pore area (%). For each trial, 5 carrot appetizer cakes were printed and weighted. From the 5 appetizers cakes, 3 were used to determine the textural properties and 2 for the dimensional profiles and the microstructural analysis.

Table 2. Experimental design of 26 trials.

Trial	Nozzle diameter (mm)	Filling rate (%)	Baking temperature (°C)	Baking time (min)
1	4.3	70	170	30
2	5.1	85	195	25
3	5.1	55	145	15
4	3.4	55	145	25
5	2.5	70	170	20
6	3.4	55	195	25
7	5.1	85	195	15
8	3.4	85	145	25
9	3.4	85	145	15
10	4.3	70	120	20
11	5.1	55	195	15
12	3.4	85	195	25
13	6	70	170	20
14	5.1	85	145	25
15	4.3	40	170	20
16	4.3	70	220	20
17	5.1	55	145	25
18	5.1	85	145	15
19	4.3	70	170	20
20	4.3	100	170	20
21	5.1	55	195	25
22	3.4	55	145	15
23	3.4	55	195	15
24	4.3	70	170	20
25	4.3	70	170	20
26	3.4	85	195	15

2.5. Dough analysis

A texture analysis of the produced dough was performed to ensure the repeatability of the preparations. Sample of dough were prepared as described by Masbernat (2021). The maximum force was measured by a back extrusion method (piston probe with annulus gap of 1.5 mm, crosshead speed of 1mm/s, 30 mm of depth) using a texture analyzer (TaHD, Stable Micro Systems, Surrey, UK). The maximum force was 30.5 ± 5.1 N for all the dough at 20 ± 1 °C after 1 day. Moreover, the results shown that it is possible to obtain printed appetizers of good printing quality by using dough at 20 °C and having a maximum force varying from 23 to 37 N.

2.6. Analyzes of carrot appetizer cakes

2.6.1. Textural properties

For each trial, the 5 printed appetizer cakes were weighed just after the printing to compare the mass of appetizer cakes according the printing parameters and after baking in the oven to determine the mass loss (g/100g). Textural properties of appetizer cakes were also analyzed using a TAHD plus texture analyzer (Stable Micro Systems, Surrey, UK) on hour after baking. A conical probe was used to penetrate crust of appetizer cakes. Five penetrations were realized on the surface (one in the center and four around) with a penetration speed at 1 mm/s and a distance of 10 mm. Three parameters were studied: crust strength (N), mean force inside cake (N) and gradient after crust penetration (N/s). Two appetizer cakes were analyzed for each trial.

2.6.2. Dimensional profiles

A laser-based scanner (VolScan Profiler, Stable Micro Systems, Surrey, UK) with a vertical step of 0.5 mm and a rotation speed of 0.5 rps was used to determine maximum width and height of carrot appetizer cakes (Figure 2A). The maximum width and height were respectively used to represent the deformation (Figure 2B) and swelling (Figure 2C) of appetizer cakes after baking. Duplicates were realized for each trial.

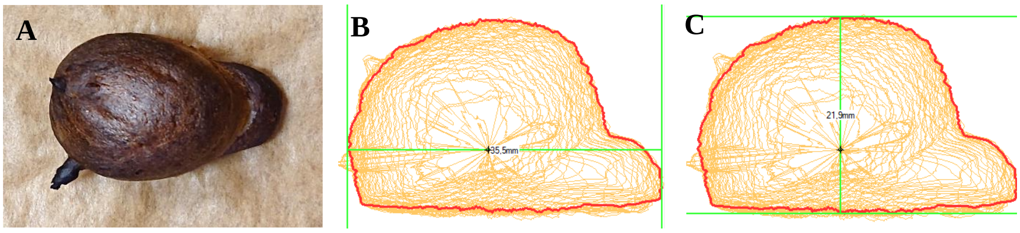


Figure 2. Example of a printed carrot appetizer cake (nozzle diameter: 5.1 mm, filling rate: 55%, baking temperature: 195°C and baking time: 25min) (A), maximum width (B) and maximum height (C) determined with Volscan Profiler.

2.6.3. Microstructural analysis

The same two printed cakes used to determine the dimensional profiles were cut in 2 part with a knife for image acquisition. Samples were placed on a flatbed scanner (HP Scanjet G31110, Hewlett-Packard, Palo Alto, CA, USA) and a black box was added on top as described by Monnet, Michon, Jeuffroy, & Blumenthal (2019). Images acquired were in full color and with a resolution of 600 dpi (Figure 3A). Scanned images were transformed by an analysis method (color threshold and isodata algorithm) using ImageJ (v1.52a) to determine the total area represented by the pore (Figure 3).

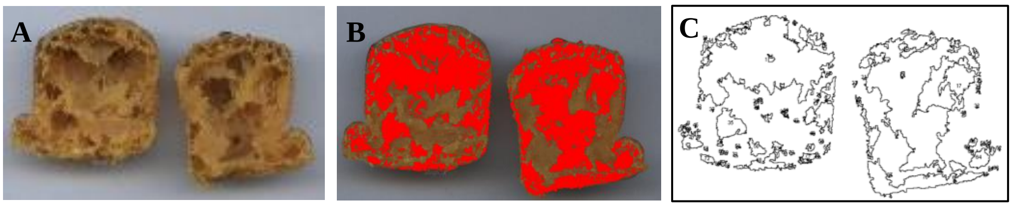


Figure 3. Scanned image (A), image after threshold (B) and result obtained by ImageJ (C).

2.7. Statistical analysis

The experimental design and statistical analysis were realized using JMP software (version 15.0, SAS Institute Inc., Cary, SC, USA). A multiple regression analysis was performed on all independent variables to evaluate their significant effects ($P \leq 0.05$) on each of the 7-response variable. The significant effects of all the independent variables were ranked in descending order by the software according to their *p* value expressed as a LogWorth value (LogWorth = − log10(*p* value)). A principle component analysis (PCA) was also performed to map printed carrot appetizer cakes according to their textural properties as principal variables and to process parameters (printing and post-processing) as explanatory variables.

3. Results and discussion

3.1. Generation of 3D-printed appetizer cakes with different texture using process parameters

Table 3 shows for each trial the 3D printing model and the carrot appetizer cake after printing, baking and cutting in half to see inside the cake. The modification of the nozzle diameter and the filling rate resulted in nine different 3D model of carrot appetizer cake which can be observed by the inside view of the 3D printing model (Table 3). After printing, as each model had one full layer on top, the differences due to the printing parameters are less obvious, but it is still possible to see the difference between each nozzle diameter used. In general, the mass of appetizer cakes after printing increased (from 40.3 to 55.7 g for 5 printed cakes) with higher nozzle diameter and filling rate, but these differences were not significant ($P > 0.05$).

During baking, the temperature were slightly different from the theoretical temperatures (± 1 °C) due to variations in oven. After baking, bigger differences such as browning, swelling and deformation of appetizer cakes are visible depending on baking time and temperature. For example, appetizer cake printed using a nozzle diameter of 3.4 mm were visually similar after baking at 145°C whatever the filling rate (55 or 85%) and the baking time (15 or 25 min). However, differences are more important between appetizer cake baked at 145°C or 195°C and the baking time seems really more important at 195°C. Similar comparisons can be seen for the appetizer cake printed using a nozzle diameter of 5.1 mm (same filling rate, baking time and temperature studied). The mass loss representing the loss of water from printed cakes during baking was mainly impacted by the post-processing parameters comparatively to the printing parameters. The differences in mass loss between each trial were not significant ($P = 0.07$), but further testing could possibly demonstrate a significant impact ($P \leq 0.05$).

Finally, after cutting in half the appetizer cakes, the inside view shows how compact or airy are the appetizer cakes. All these images demonstrates that the experimental design used in this study generate a wide range of 3D-printed appetizer cakes in terms of color, shape, texture and microstructure. Also, a good printing quality was observed for all trials (appetizer cake after printing), but the visual quality of the appetizer cakes after baking were impacted by printing and post-processing parameters.

Table 3. Impact of each printing and post-processing parameters studied on the 3D printing model and the carrot appetizer cake: after printing, after baking and after being scanned.

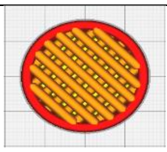
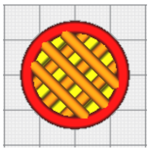
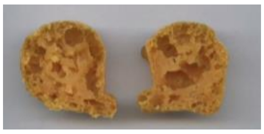
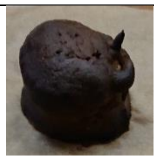
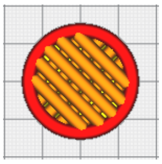
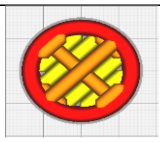
Nozzle (mm)	Filling (%)	Inside view of 3D model	Appetizer cake after printing	Baking temperature (°C)	Baking time (min)	Appetizer cake after baking	Scanned image of appetizer cake
2.5	70			170	20		
3.4	55			145	15		
				145	25		
				195	15		
				195	25		
	85			145	15		
				145	25		
				195	15		
				195	25		
4.3	40			170	20		

Table 3. (*Continued*)

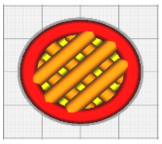
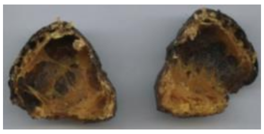
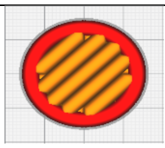
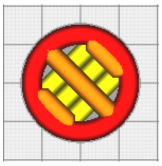
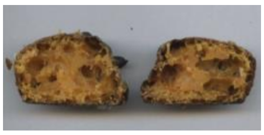
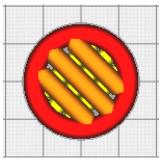
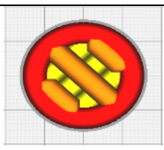
Nozzle (mm)	Filling (%)	Inside view of 3D model	Appetizer cake after printing	Baking temperature (°C)	Baking time (min)	Appetizer cake after baking	Scanned image of appetizer cake
				120	20		
				170	10		
4.3	70			170	20		
				170	30		
				220	20		
	100			170	20		
				145	15		
				145	25		
5.1	55			195	15		
				195	25		

Table 3. (*Continued*)

Nozzle (mm)	Filling (%)	Inside view of 3D model	Appetizer cake after printing	Baking temperature (°C)	Baking time (min)	Appetizer cake after baking	Scanned image of appetizer cake
5.1	85			145	15		
				145	25		
				195	15		
				195	25		
6	70			170	20		

3.2. Interactions between process parameters: how do they modify the texture of the printed cakes?

Figure 4 shows results of principal component analysis (PCA) realized to map printed appetizer cakes according to the textural and microstructural properties (dependent and principal variables) and the printing and post-processing parameters (independent and explanatory variables) of cakes. The principal components 1 and 2 explain 76.6 % of the total variance. Component 1 was related to baking temperature and baking time and explained the majority of the textural and microstructural properties (54.5 %) (Figure 4a). The increase in baking time and temperature increases significantly ($P \leq 0.05$) the water loss (mass loss), the total pore area inside the cakes, the strength of the crust as well as the mean firmness inside the cakes. However, under these high baking conditions the difference in strength between the crust and the inside cake is lower (gradient after crust penetration). These changes in textural properties can be mostly explained by the reduction of the water content during baking.

Only the mass after printing and the dimensional profiles (maximum height and width) were supported by component 2 (22.1 %) and were mostly related to the filing rate. A higher fill rate leads to a higher mass after printing and a greater height (swelling) and width (deformation) of the cakes after baking. These results shows that the final shape of the printed cake can be controlled by the filling rate whereas the results of the literature indicated rather to modify the baking parameters or the composition of recipes to control deformation or swelling (Kim et al., 2018; Severini et al., 2018). Although the impact of the filling rate is significant ($P \leq 0.05$), this printing parameter does not seem to explain the differences in textural and microstructural properties observed on the PCA (Figure 4). An impact of the filling rate has been demonstrated by Severini et al. (2016) on the hardness of 3D-printed and cooked snacks (infill levels of 10, 15 and 20 %) and by Liu et al., (2018) on the hardness, gumminess, firmness and Young's modulus of printed mashed potatoes (infill levels of 10, 40 and 70 %). The use of higher filling rate (from 40 to 100 %) in our study would therefore limit the potential impact of this printing parameter on the textural properties.

The nozzle diameter also have a significant impact ($P \leq 0.05$) on textural, microstructural and shape properties of 3D-printed cakes, but this parameter was rather orthogonal to all the principal variables on the PCA (Figure 4). In addition, three significant interactions ($P \leq 0.05$) were observed between the process parameters. Figure 5 shows an example of interactions observed for the crust strength. The interaction between the post-processing parameters had the lowest P value (LogWorth = 3.119), comparatively the two other interactions between the nozzle diameter and the baking time (LogWorth = 1.702) or the baking temperature (LogWorth = 1.761). These interactions demonstrate that when using high temperature baking or longer times of baking, the choice of nozzle diameter influences the textural properties of 3D-printed cakes. For example, to avoid the formation of an excessively resistant crust (high crust strength) when baking at high temperature (195 °C) or for long duration (25 min), it would be preferable to use a larger nozzle diameter (5 mm) (Figure 5). No significant interaction with the filling rate was observed. Similar interactions were observed for gradient after crust penetration and mean force inside cake. However, interactions between the nozzle diameter and the post-processing parameters were less obvious for the total pore area and the dimensional profile as presented in Figure 6 for the maximum width. The impact of the nozzle diameter on print quality (visual appearance, shape, dimension) has already been demonstrated by other studies using dough (Liu, Saeed, & Lan, 2019; Yang, Zhang, Fang, & Liu, 2018), fiber-rich snack (Krishnaraj, Anukiruthika, Choudhary, Moses, & Anandharamakrishnan, 2019), surimi gel (Wang et al., 2018) or lemon juice gel (Yang et al., 2018). In this study, we demonstrate for the first time the importance of the nozzle diameter mainly on the textural and microstructural properties of printed and baked foods.

Figure 6 also shows that the interaction between the post-processing parameters was different from that observed for the textural and microstructural properties. More specifically, these properties were impacted by baking time and temperature when higher conditions were used comparatively to dimensional profile that are impacted by lower and higher baking conditions. In addition, a trend (P = 0.09) was observed for an interaction between the printing parameters mainly concerning the dimensional profile of the printed cakes (Figure 6). These results show that the choice of the nozzle diameter could be important when using a high filling rate to better control the deformation of the cakes. Similar interactions were observed for the maximum height, but further study would be needed to better understand this potential interaction.

3.3. Back-engineering approach : from textural, microstructural and shape properties to process parameters

In our study, we applied the back-engineering approach and more precisely the desirability function as used by Monnet et al. (2021). This method allows determining the process parameters to be used to target specific properties of 3D printed cakes using multiple factors. Figure 7 shows optimal parameters to use according to specific shape, microstructural and textural properties. The choice of these specific properties has been simulated to present an example, but different values for each of the properties could obviously be selected. We chose a specific percentage of total pore area (not too compact or too airy), a mean crust strength (not too friable or too resistant crust) as well as a mean gradient after penetration and a mean force inside the cake. For the shape properties, we chose a maximum height to maximize swelling and a specific width to minimize the deformation beyond the expected diameter of 30 mm of printed appetizer cakes. In this case, a good desirability of 93.7 % is obtained and the optimal parameters to use are a nozzle diameter of 3.4 mm, a filling rate of 71 %, a baking temperature at 177 °C and baking time of 25 min. This tool can therefore be used directly to predict the printing and post-processing parameters to use to modulate properties of printed carrot appetizer cakes.

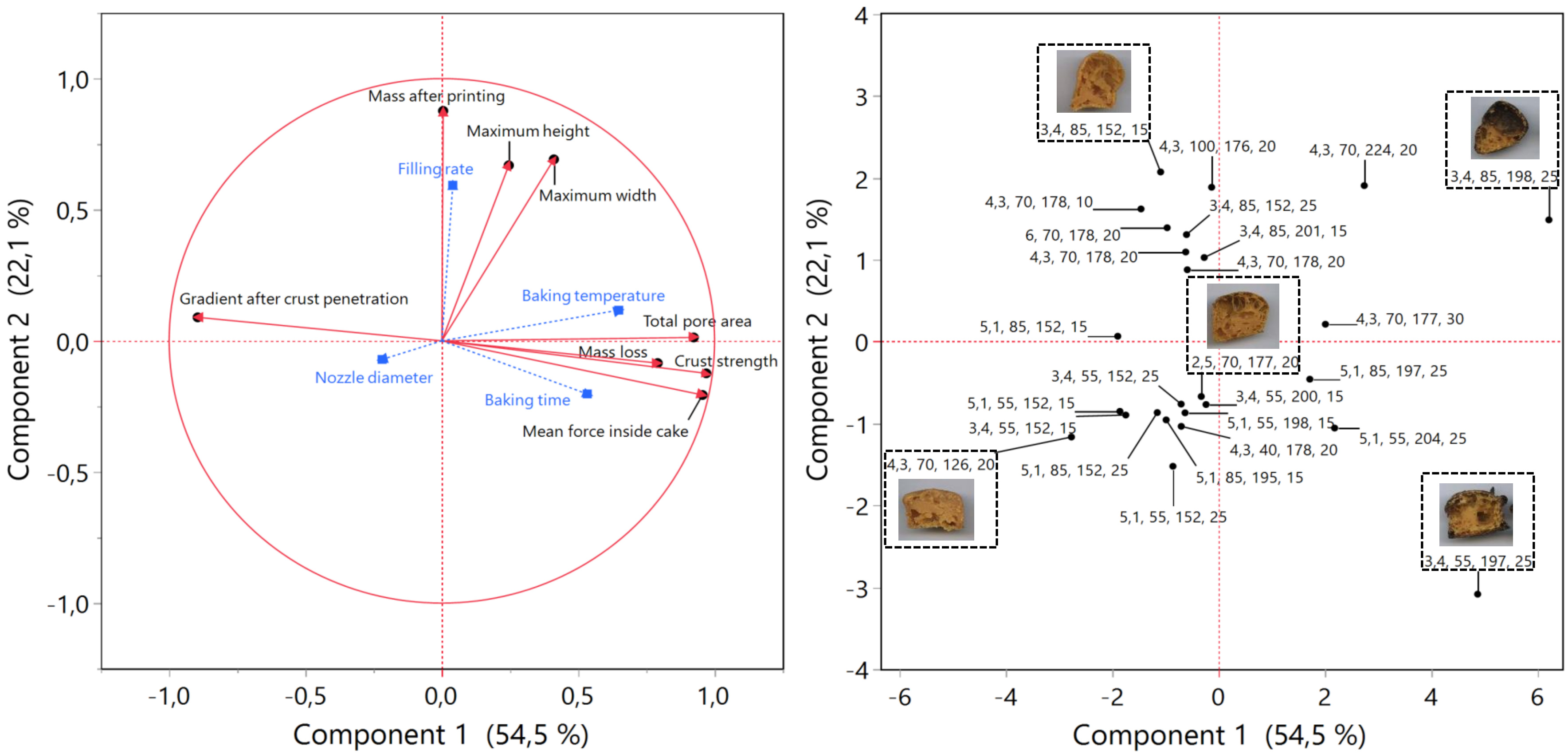


Figure 4. Principal component analysis: Correlation circle (A) and PCA map (B) of printed appetizer cakes (each trial identified by: nozzle diameter, filling rate, baking temperature and baking time). Principal variables were shape, textural and microstructural properties (red lines) and explanatory variables were printing and post-processing parameters (blue dashed lines).

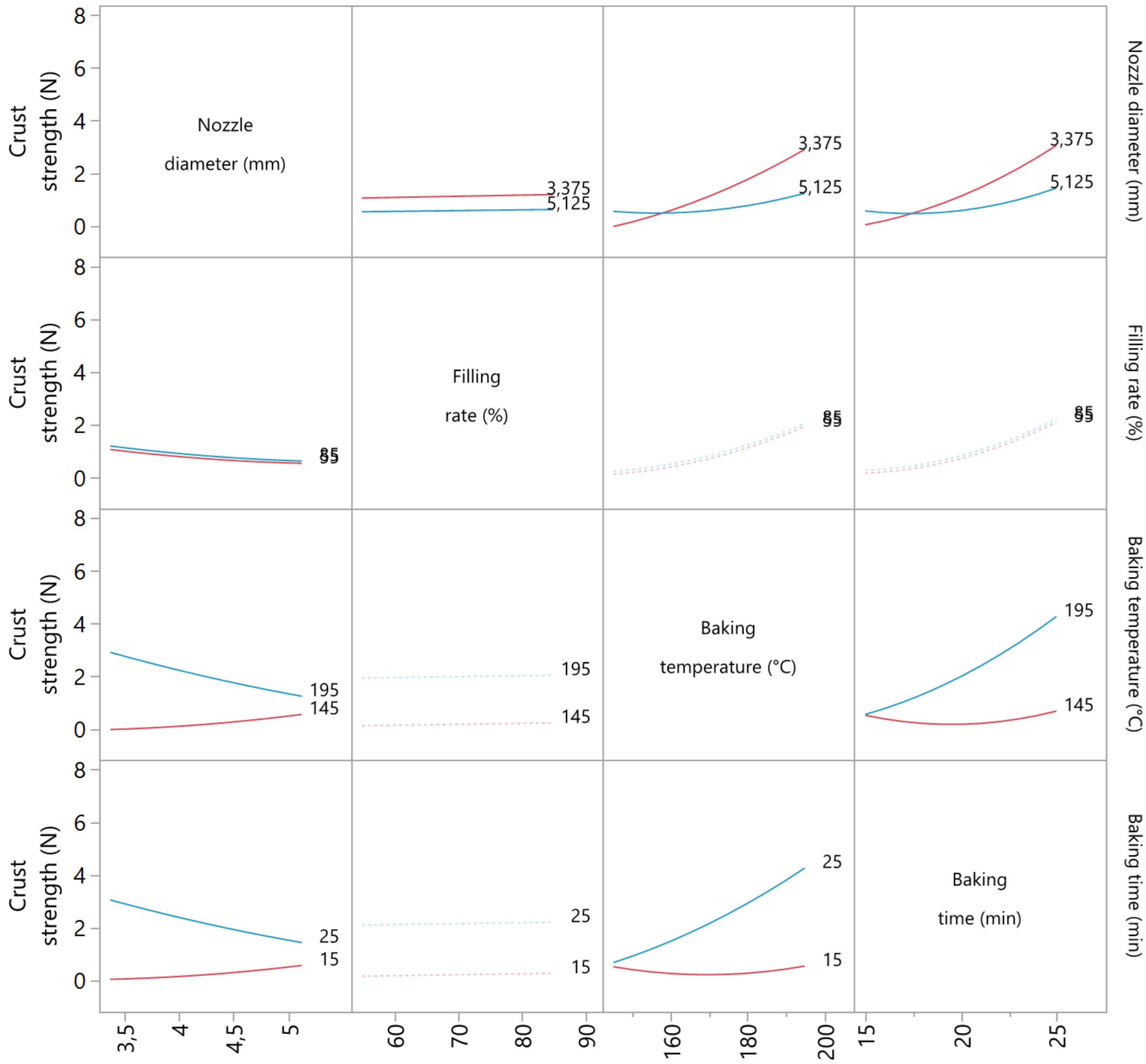


Figure 5. Interactions between process parameters and crust strength. Continuous lines represent significant interactions ($P \leq 0.05$) except for the interaction between the nozzle diameter and the filling rate which is a trend at $P = 0.09$. Dotted lines represent non-significant interactions ($P > 0.05$).

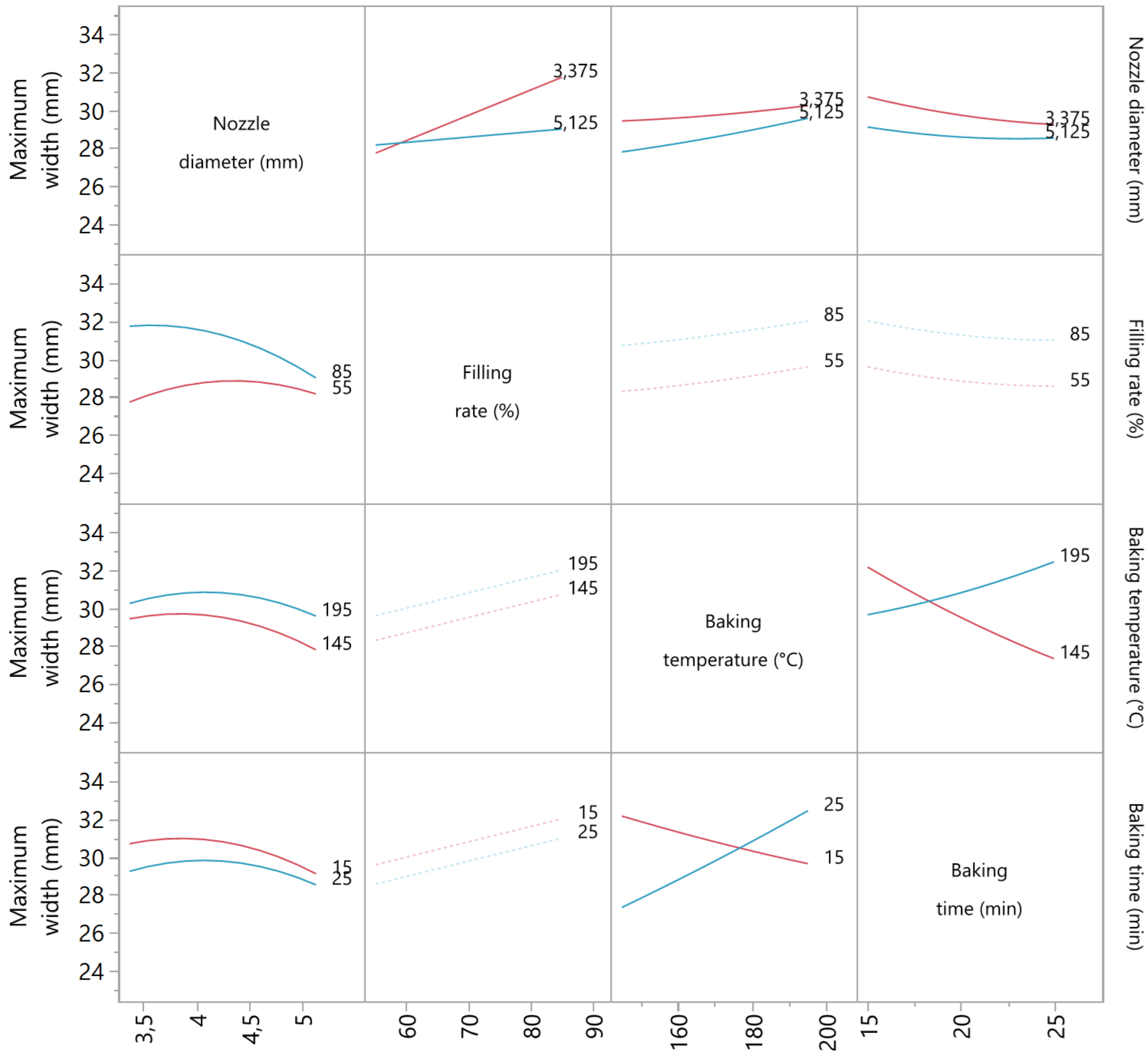


Figure 6. Interactions between process parameters and maximum width. Continuous lines represent significant interactions ($P \leq 0.05$) except for the interaction between the nozzle diameter and the filling rate which is a trend at $P = 0.09$. Dotted lines represent non-significant interactions ($P > 0.05$).

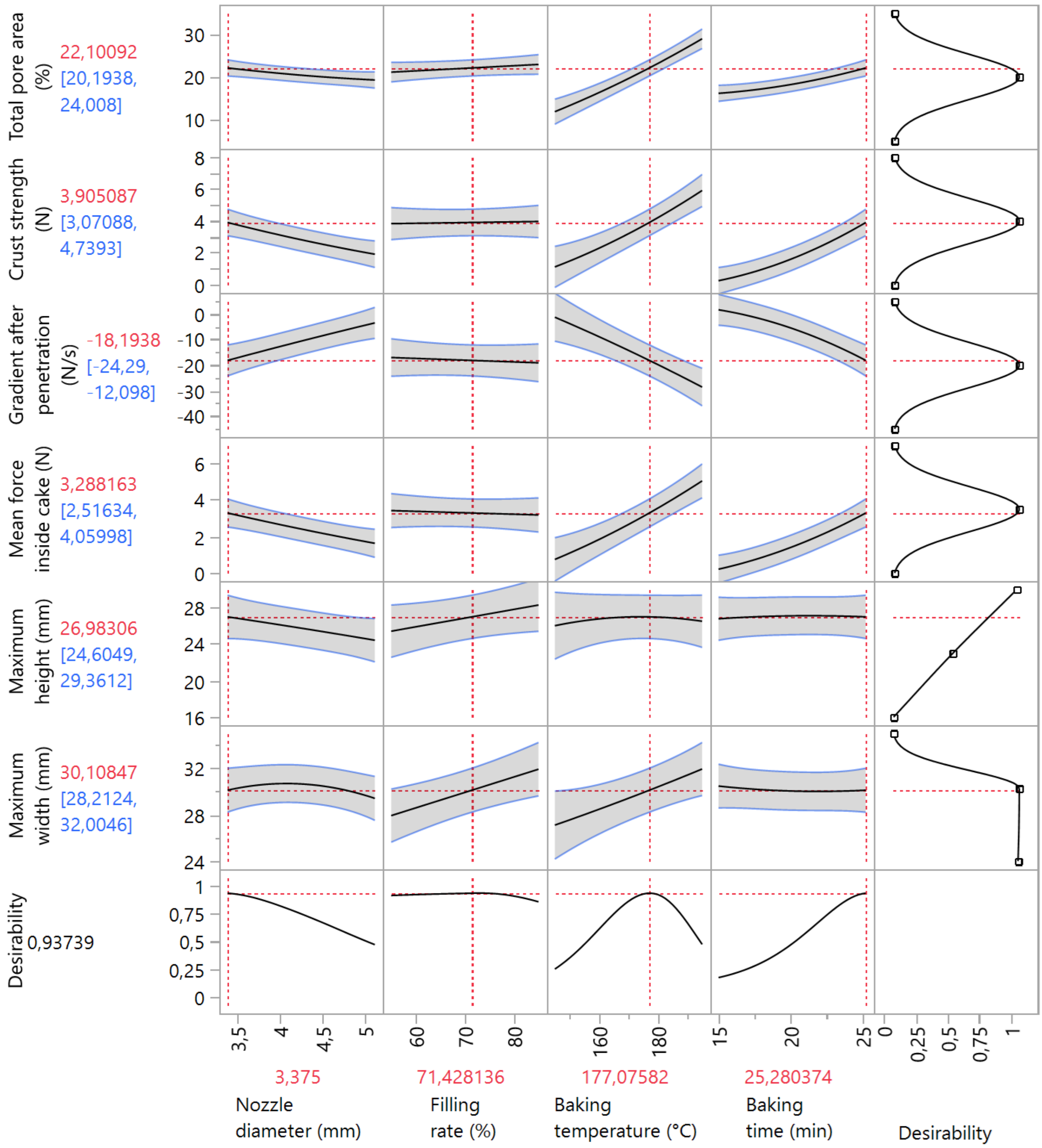


Figure 7. Maximisation of desirability to obtain specific textural, microstructural and shape properties of printed carrot appetizer cakes including all dependent variables analyzed.

4. Conclusions

This study demonstrated the impact of printing and post-processing parameters on 3D-printed appetizer cakes using a carrot-puree-based dough as food-ink model and a 3D-food printer prototype. The changes in texture, microstructure and shape of 3D-printed cakes occurs mainly because of the baking time and temperature. However, this study also identified the impact of the printing parameters on the baked cakes. The filling rate can modulate the final shape of the cake by controlling their swelling and deformation. The nozzle diameter also modifies all the properties studied but its impact was mainly observed in interaction with the baking parameters (time and temperature) which can be an interesting lever to customize the texture of the printed foods. Obviously, other printing parameters could be studied in a future research such as the shape of the printing model (infinite possibility), the thickness of the outer wall as well as the filling pattern. Other food-ink should also be studied to validate the application of these results to a wider range of products.

In addition, a predictive model is proposed and allows to target specific textural, microstructural or shape properties of 3D-printed appetizer cakes. These results can be used for the development and optimization of 3D cake printing. In future studies, a sensory characterization of these printed products as well as a study of visual and sensory appreciation by consumers should be performed to supplement the information obtained by the instrumental methods and to determine the properties that meet consumer expectations.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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