3D opportunity serves it up

Additive manufacturing and food

A Deloitte series on additive manufacturing

About the authors

Kim Porter

Kim Porter is a principal with Deloitte Consulting LLP, where she serves as the national sector leader for consumer products. In her role, she advises CP manufacturers on how to capitalize on the wave of digital/technology innovation disrupting the sector to drive growth.

Jarrod Phipps

Jarrod Phipps is a senior manager with Deloitte Consulting LLP. His work focuses on helping clients identify and adopt emerging disruptive trends such as 3D printing, artificial intelligence, robotics, crowdsourcing, and others.

Adam Szepkouski

Adam Szepkouski is a consultant with Deloitte Consulting LLP. He helps clients identify and categorize the applications of exponential technological change and understand their disruptive potential on the business landscape of today.

Sam Abidi

Sam Abidi is a business technology analyst with Deloitte Consulting LLP. His work focuses on quantitative strategy within the innovation and R&D domains, helping clients rationalize and expedite R&D portfolios in the health sector.

Deloitte Consulting LLP's supply chain and manufacturing operations practice helps companies understand and address opportunities to apply advanced manufacturing technologies to impact their businesses' performance, innovation, and growth. Our insights into additive manufacturing allow us to help organizations reassess their people, process, technology, and innovation strategies in light of this emerging set of technologies. Contact the authors for more information, or read more about our alliance with 3D Systems and our 3D Printing Discovery Center on www.deloitte.com.

Contents

Introduction

WHAT will our spaceship-dwelling descendants eat? If science fiction is any guide, machines such as *Star Trek's* "replicators"[1] will be able to generate any desired foodstuff on demand. We're a long way from that reality—three centuries, in the *Star Trek* universe—but manufacturers have taken steps in that direction, with real-world implications for the short as well as long term.

Current benefits of edible AM include product differentiation, product customization, and direct-to-consumer relationships.

Few readers would be surprised to learn that inventors and manufacturers have experimented with printing food—it's a natural evolution in the technology of additive manufacturing (AM), commonly referred to as 3D printing. For some 30 years, AM—a manufacturing technique that builds objects layer by layer—has focused on using polymers (for example, plastics) and, more recently, metals. In the past few years, experimental materials, including edible ingredients, have emerged as well. Accompanying that expansion, AM is coming to encompass a wider set of applications, ranging from aerospace cooling ducts[2] to 3D-printed pizzas.[3]

True, at this point, edible AM printing is more niche or novelty than an industry game-changer: Restaurant chains and packaged-food giants seem unlikely to convert entire production lines to printing most of what customers eat and buy anytime soon. But AM using edible materials allows food makers to explore the customization of their otherwise mass-produced and, in many cases, commoditized products. Deloitte's research has presented that the current benefits of edible AM include product differentiation, product customization, and direct-to-consumer relationships. There are indications that this may lead to more evolutionary capabilities, such as the creation of unique food formulations for dietary needs,[4] simplified distribution into hard-to-reach locations, and customized medical/nutritional supplements.[5]

In this article, we seek to inform readers about the current state and future trends related to AM and food. We will also examine some of the challenges facing companies that are looking to leverage AM technologies in food.

We'll begin by explaining the different printing processes involved. Although AM technology principles tend to be the same whether the materials are edible or polymer, it is important to understand the similarities and differences of the printing processes, to develop a more complete grasp of the technology's capabilities. Then we'll move on to show how AM food printing fits into the four paths of Deloitte's well-established additive manufacturing framework.[6]

Keep in mind that AM technology, in food and elsewhere, is in the early stages; companies continue investing in R&D and regularly develop new capabilities, so the examples cited here do not represent the end of the story. When it comes to edible 3D printing, science fiction—at least to some degree—may become fact sooner than expected.

How to print food

DIFFERENT AM technologies offer advantages and disadvantages to possible applications, balancing levels of customization, capital requirements, and precision. The Deloitte University Press article *The 3D opportunity primer*[7] lays out the seven generally recognized AM processes. The choice of AM technology depends on the parameters of the job at hand: quantity, time constraints, material, whether the item requires multiple materials, and so on. In the case of edible printing, the standard process descriptions apply. The key to determine which process to use is the nature of the materials being printed. Even more than with metals and polymers, there are a vast number of different foods, each with a unique combination of consistency, malleability, and adhesion.[8]

AM-enabled food applications can generally be grouped into two main areas: direct printing and mold printing. Direct printing involves growing an object layer by layer (usually through extrusion or "binder jetting"); mold printing involves creating a mold from a different material and then using it as a cast for the actual material. Within each of these groups, variations on technique allow for a broad array of capabilities.

Approaches for direct printing of food

Direct printing through extrusion

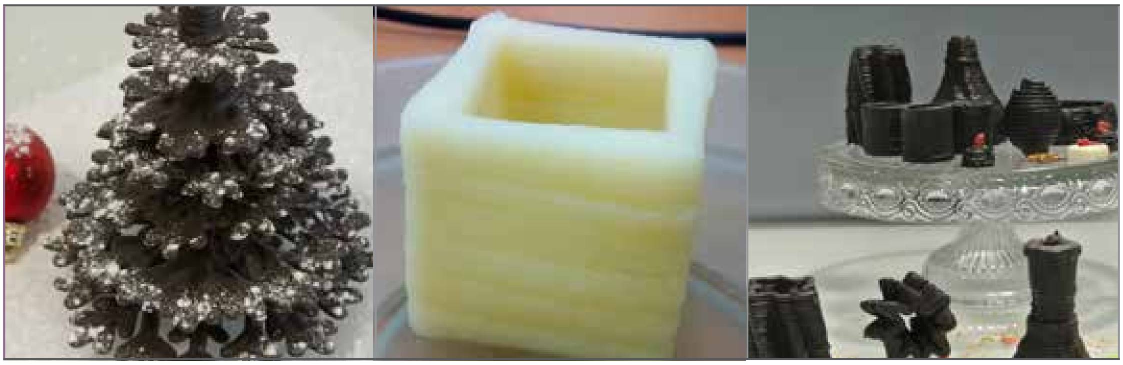
WHEN calculated by products offered, material extrusion constitutes one of the most common AM processes.[9] Typically used for the manufacture of polymer-based items, companies looking to create one-off versions of their edible products have also picked up the technology. A number of companies and organizations, including NASA[10] and 3D Systems,[11] have designed and demonstrated extrusion-based food-printing machines.[12]

Material extrusion processes offer several advantages. First, they support a wide array of foods, including any that can be extruded through a nozzle and maintain its geometry post-extrusion.[13] Second, the extrusion method allows for a high degree of freedom as to the designs that can be printed, since object features do not have to be removed from a mold.[14] Third, since no mold is required, costs are limited to the digital design of the object, the machine's amortized cost, and the food-based inputs.[15] Given that many applications involve the consumer creating their own design, this method offers the promise of delivering variable-cost only production, enabling a wide range of customization.

Chocolate, with compliant physical characteristics, is one of the most common foods used for extrusion printing, presenting an opportunity to deliver branding messages and creative design. For example, the University of West of England has printed intricately detailed chocolate doilies, demonstrating precision unavailable with traditional food-manufacturing techniques.[16] Researchers there have also successfully printed materials such as cream cheese and mashed potatoes (figure 1).[17]

AM producers have more recently begun offering extrusion-based systems with multiple nozzles, allowing end users to combine materials, with the goal of creating full entrees rather than single-component foodstuffs. Foodini's creation of an AM pizza[18] offers a good example of this technique: By depositing the dough, sauce, and then cheese onto a cooking surface, the entire process of pizza-making can be automated and customized to accommodate portion requirements (see figure 2).

Figure 1. Printed food in chocolate and mashed potatoes



Source: Natural Machines. Reprinted with permission.

Figure 2. Three stages of a printed pizza

Source: Natural Machines. Reprinted with permission.

This idea of combining multiple materials can be extended to foods such as cakes, for which printers can mix and then cook multiple batters, signaling possibilities for further applications by manufacturers and end users.

Direct printing through binder jetting

Binder jetting is another common approach to AM-based food production.[19] This process utilizes a powder and binding agent: For each level of an object, a thin layer of powder is deposited on a print bed. Then, a printer head, moving like a standard inkjet printer, applies a binding agent in a pattern predefined by the 3D shape being created (see figure 3).[20] An advantage of binder-jetting processes is the ability to use colored binding agents, thus allowing for the design of full-color objects. Translating this process to food, AM manufacturers such as 3D Systems have created printers that replace polymer or metal powders with sugar crystals, and the binding agent with a mixture of water and alcohol, for a printing process that can fashion complex, precise sugar sculptures. This technology presents a branding opportunity for producers of candy and sweets to differentiate their products,[21] particularly since the printing allows precisely drawn logos and photos.[22] Notably, powder-based sugar creations are fragile and difficult to transport, encouraging applications at or close to the point of consumption—for example, a restaurant, bakery, or hotel.

Figure 3. Complex geometries in additively manufactured food

Source: 3D Systems. Reprinted with permission.

Mold printing

MOLD printing offers an alternative, indirect, and sometimes simpler approach to AM-enabled food production than direct printing. Since AM technology has its roots in the printing of photo-polymers, the techniques and printers capable of printing these materials enjoy a higher level of maturity. Today, 3D printers can produce a mold directly out of food-safe Class VI FDA-approved material using common stereolithography processes; the process involves designing the product's shape using computer-aided design software and then printing a negative of the design (that is, a mold).[23]

An example of molded printing is the shaping of flavored gelatin, a material well-suited to this form of 3D printing because it cannot be easily extruded but, rather, begins in a liquid form. A few companies are experimenting with scanning customers' faces and bodies to print molds to then create chocolate or jelly candies.[24] With a reusable mold, this type of edible printing can be both simple and inexpensive, even for foods, such as chocolate, that will work with extruded technology.

Options for deploying additive manufacturing

TO help understand how organizations leverage AM as a general set of technologies, Deloitte studied how enterprises deploy these technologies to change the way in which they engage the market. Through our analysis, we developed an additive manufacturing framework that helps organize applications and disentangle the various impacts of the technology.[25]

The framework identifies four tactical paths to pursue, depending on each organization's needs, goals, and circumstances (see figure 4 for an illustration of the framework).

- **Path I, stasis**: Companies do not seek radical alterations in either supply chains or products but may explore AM technologies to improve value delivery for current products within existing supply chains.

- **Path II, supply chain evolution**: Companies take advantage of scale economics offered by AM as a potential enabler of transformation for the products they offer.

- **Path III, product evolution**: Companies take advantage of the scope economics

Figure 4. Deloitte's additive manufacturing framework

Graphic: Deloitte University Press | DUPress.com offered by AM technologies to achieve new levels of performance or innovation in the products they offer.

- **Path IV, business model evolution**: Companies alter both supply chains and products in the pursuit of new business models.

Using this framework as a lens, we reviewed company activity related to AM and food, as well as relevant research literature to identify key trends relevant to food-based businesses. As AM food printing continues its development and maturity, applications are poised to evolve. This analysis seeks to represent our current view of additive manufacturing as an opportunity for food businesses.

As AM food printing continues its development and maturity, applications are poised to evolve.

Path I: Stasis

Path I in the AM framework contemplates applications that do not aim to radically change either supply chains or products. Here, companies attempt to deploy AM technology in support of existing operations. That does not mean, however, that interesting and valuable opportunities do not exist: For example, cooks and kitchens have used molds in food production for centuries, and many companies face choices about when to create new molds and what level of customization is most appropriate. This is an evergreen issue in any industry in which "tooling" is important.[26] Deployment of AM for molded food production offers the opportunity to create the custom, reusable gelatin molds described above. The result may be the delivery of molds more quickly and with lower investment—as well as with more elaborate options.

We may see companies using edible printing to enhance preparation or maintenance in current processes. And though AM may deliver real value to current operations, many see other value through the impacts that the technology can have on supply chains (path II), products (path III), and entirely new business models (path IV).

Path II: Supply chain evolution

Path II of the AM framework focuses on impacts, leaving the end product, from the consumer's perspective, unaltered while changing the supply chain and mode of delivery. This path represents a step forward for food companies looking to incorporate edible printing while maintaining existing products. Companies might, for example, experiment with making similar—or even identical—products at remote sites, altering supply chains and delivery systems.

In our analysis, we find it a challenge to identify pure supply chain plays in the edible printing arena.[27] This is because, so often, it is the *combination* of product and delivery mode that makes up the food product's total goods-and-service offering. As the upcoming discussion will show, many companies are contemplating operating models that offer the potential to change the location of food preparation and service through AM deployment. Overwhelmingly, however, these models also incorporate changes to products (typically through customization) that move the overall characterization of the offering onto path IV (business-model evolution) of our AM framework.

For an appropriate path II example, we suggest consideration of NASA's work investigating ways to improve astronauts' life-support system, which include feeding the crew during long deep-space missions.[28] NASA's Advanced Food Technology program has been tasked with finding (literally) pie-in-the-sky solutions that minimize crew cook time and physical space; AM is posited to allow for variety in food options as well as ensuring delivery of necessary nutrients. The US military is also researching the use of mobile 3D food printers to help with rationing;[29] the technology would provide a more varied menu for soldiers currently limited to their predetermined MRE (Meal, Ready-to-Eat) supply. In each case, logisticians face a need for predictable, nutritious foodstuffs in environments (space, combat) where more traditional methods of storage and preparation are unavailable.

Path III: Product evolution

Controlling the *form* food takes

Path III (product evolution) represents an area of increased activity for companies. On this path, organizations innovate by altering their products' structure, design, and consumption experience by introducing new and interesting geometries, flavors, or ingredient combinations. Since this path implies changes to only the product, food makers will continue to produce their products at a centralized facility and distribute through traditional channels to their consumers.

As one example, the Italian food company Barilla created a marketing campaign inspired by 3D printing,[30] featuring a competition to submit ideas and designs to shape Barilla's next pasta. Three winning contestants submitted designs of never-seen-before pasta, such as a crater-riddled moon and a complex cone vortex; the grand prize submission was a rose that blossoms when placed in boiling water.

In another example, previously mentioned Barcelona-based company Natural Machines is developing a multi-ingredient food printer, the Foodini.[31] The microwave-sized machine can use either pre-packaged or owner-created raw materials to construct meals such as pizza, ravioli, and hamburgers (figure 5). At present, the Foodini is not capable of cooking the meal—it can prepare the meal only up to the point at which the food is ready to be cooked.

AM has also inspired startups such as the crowdfunded PancakeBot, whose home-use design allows owners to sketch their own pancake creations to upload to a printer, which extrudes pancake batter onto its own hot plate.[32]

Controlling the *content* of food

Food-system manufacturers are also experimenting with ways to modify more than just the form of the edibles produced. Using AM to create food products that can provide personalized nutrition is also currently in the testing phase. Applications here relate to specific groups of individuals such as athletes, astronauts, and hospital patients, who require

Figure 5. Foodini food printing device

Source: Natural Machines. Reprinted with permission.

precise nutritional contents in order to optimize their health.[33] Nestlé offered an example of this type of application with its 2013 launch of the "Iron Man" project: The project aims to develop profiles that analyze levels of essential nutrients unique to an individual, with the intent of synthesizing bespoke food and medicine.[34]

There are also some companies that see significant opportunities in the unique medical needs of elderly or physically challenged adults. One example serves elderly customers who have difficulty swallowing. German company Biozoon is developing a 3D "Smoothfood" project that aims to provide individualized nutritional meals with a jelly-like texture that resembles solid food but is dissolvable in the mouth for an easier swallow.[35]

These examples notwithstanding, AM's potential benefits suggest even greater opportunities in combining product innovation with altered supply chains to create entirely new food business models. Therefore, while path III offers interesting possibilities (and ones that may emerge as increasingly relevant), many see more promise along the path IV framework.

Path IV: Business model evolution

Organizations whose AM venture takes them down path IV will aim to use the technology to change their products as well as the ways in which those products find their way to market. Path IV is where many breakthrough opportunities are emerging to reinvigorate brands, categories, and products, or to deliver fundamentally new consumption experiences to the end consumer.

Hershey's, for example, has been testing the waters of 3D printing: In partnership with 3D Systems, the company has stationed an extrusion printer in the company's "Chocolate World" attraction in Hershey, PA.[36] The interactive exhibit allows visitors to design their own chocolate creations while watching the printer in action. In addition to working to delight visitors, the company expects the demonstration to offer insight into customer preferences.

Grocery stores—seeking ways to differentiate themselves and to simplify complex supply chains—are also considering applications for 3D food printers. In early 2015, for example, Dutch supermarket Albert Heijn launched a chocolate extruding printer in its bakery department, expanding custom cake-decorating services.[37] By extension, vending-machine opportunities may also offer potential: At the 2014 South by Southwest festival, an Oreo vending-machine prototype fashioned custom cookies on the spot based on Twitter trends.[38]

Closer to home, individual households may soon have the ability to print complete meals. With the ChefJet, 3D Systems has introduced a scalable, multiservice food-printing prototype,[39] aiming for ease of use and defined processes that help with cleanliness and freshness in daily consumption.

Hybrid product/supply chain models are also starting to emerge. These approaches play to consumers' growing interest in a wide range of online shopping options, including delivery of prepared food and grocery items. For example, Amsterdam's MELT Ice Pops allows consumers to design customized frozen desserts on an online interface, creating a final product that can be delivered to their doorstep.[40] Distribution networks and easy-to-use online interfaces may allow for an efficient mix of on-site and centralized fulfillment.

Finally, emerging markets may also see benefits from AM food technology. The "Insects au Gratin" project looks to capture the nutrients of edible insects that are dried and ground into powder, then combined with water and a gelling agent to print food (in customizable and presumably appetizing shapes) rich with necessary nutrients.[41] In areas with limited local food sources and unreliable supply routes, organizations may be able to tap a supply of insects to satisfy dietary needs.

Challenges and barriers to overcome

WHETHER in households, grocery stores, vending machines, or in space, adopting AM for designing and manufacturing food faces specific challenges. Leaders seeking to deploy these technologies in food service may be well advised to consider them as they make plans to advance their AM strategies. In particular, interested managers should consider constraints related to regulation, food safety, and availability of ingredients.

Regulation

Food production takes place in many different contexts: Venues as diverse as restaurants, vending machines, and grocery stores may one day host 3D printers. It is, therefore, important to consider how regulatory agencies such as the US Food and Drug Administration categorize these venues, and what impact their regulations will have on production.

For example, the FDA currently differentiates between locations that "produce" food and those that merely sell packaged food. Once a package seller begins interacting with raw, non-packaged food, it may expect to face a new regulatory regime. Organizations that choose to make this transition will need to consider issues such as cleaning parameters, training of in-store personnel, and regular inspection.[42] With no regulations currently in place for AM food, the FDA will no doubt be establishing—in collaboration with companies and other governmental entities—guidelines for specific foods, facility inspections, and personnel training. Restaurants, with well-defined regulations and a need for consistent outputs, will take a particular interest in AM guidelines.

Leaders seeking to deploy these technologies in food service may be well advised to consider them as they make plans to advance their AM strategies.

Food safety/shelf life

Another consideration for 3D-printed food and, in particular, extruded foods has to do with temperature fluctuations during the extrusion process. Traditionally, when material is extruded, it must be heated to create a substance sufficiently malleable to pass through the extrusion nozzle. This heating and cooling process may represent a health concern for food. Heating and/or cooking may make food susceptible to microbial growth, bacteria, or fungus, therefore decreasing its effective shelf life. For extruding food, companies will need to adhere to FDA guidelines regarding appropriate food temperatures and approved shelf life.[43]

The prototypes of 3D food printers require careful calibration of multiple parameters, each dependent on the particular batch of food.

Different ingredients carry different shelf lives, and packaging may be a factor. Alternatively, we recognize that one key advantage of edible printing, whether at-home or in-store, is the ability to fashion food items only hours—or less—before sale or consumption, so shelf life may matter much less than for traditionally and centrally manufactured items.

Ingredient limitations

Not every type of food can be printed. Unlike other AM applications that extrude only a single material, printing of food often requires multiple ingredients, ranging from processed components such as cheese, sauce, or dough to more elemental ingredients such as sugars, proteins, and carbohydrates. Due to varying storage and temperature requirements and chemical compositions, it may be impractical to place these ingredients all in one container. A potential workaround is for the user to manually prepare ingredients at the time of use. Unmanned systems such as vending machines would require increased levels of automation and regular cleaning, but perhaps not much more than the coin-operated coffee dispensers that companies introduced back in the 1940s.

The variety and quality of ingredients are unavoidably and (for some) disappointingly limited, since creating an organic product, such as a whole carrot or a filet mignon, from scratch is still very much science fiction. For now, to approximate meat, a printer would likely construct a consumable protein by mixing a protein powder with water and then shaping the resulting paste into a form that attempts to mimic its natural counterpart. Both home and retail AM users are expected to continue looking for further development with respect to variety in ingredients, among other areas in edible printing.[44]

Conclusion

WILL additive manufacturing disrupt the food industry in ways similar to which it promises to shake up other industries? Compared with urgent-care medical supplies or low-demand auto parts, the challenges that AM aims to address for the food industry seem less clear, more suited to novelty applications—for example, customized Oreos—than those central to big companies' products or supply chains. When shoppers can choose from dozens of varieties of inexpensive frozen pizzas, what is the advantage to being able to *print* one?

That said, there's little question that 3D printing will continue to evolve in the food industry, perhaps in ways as yet unforeseen. As AM technology continues its evolution, initial adopters seeking to move forward should consider following a series of process steps, as outlined in figure 6.

From our perspective, initial adoption will come from those companies focused on product differentiation, product customization, and direct-to-consumer relationships; others will aim to fill consumers' unique dietary needs and simplify distribution to hard-to-reach locations. We will see AM penetrating markets from small local bakeries to multinational food distributors, while restaurants and hospitality businesses will surely find useful applications. The decision of which tactical path to follow will depend on a company's internal strategy, driven by product mix, distribution models, and the decisions of value-chain partners.

And as the edible printing market matures and becomes integral to some companies' business models, they will demand innovation, sooner rather than later. Researchers and scientists may never quite attain *Star Trek* levels of "tea, Earl Grey, hot!" at the touch of a button, but there's no reason not to aim high.

Figure 6. An approach to effective additive manufacturing adoption

Step	Action	Considerations
1. Evaluate	***Evaluate*** where in an organization an additive manufacturing solution may fit	• Food printing approach • Product differentiation • Product customization • Direct-to-customer relationships
2. Rationalize	Internally ***rationalize*** the need to determine whether an additive manufacturing solution should be pursued	• Additive manufacturing framework – Distribution strategy – Product mix – Value chain decisions • Internal strategy
3. Roadmap	Create a ***roadmap*** for implementation that outlines expectations, capabilities, and timing	• Innovator landscape • Internal capabilities • Ecosystem partners • External tools • External capabilities
4. Pilot/scale	Pilot solution to a targeted area and then ***scale*** solution to the broader organization	• Internal communication • External communication • Effective pilot location

Understanding the correct application of the additive manufacturing framework can smooth the path to successful adoption.

Endnotes

1. *Star Trek*, "Replicator," http://www.startrek.com/database_article/replicator.
2. *Economist* "3D printing scales up," September 7, 2013, www.economist.com/news/technology-quarterly/21584447-digital-manufacturing-there-lot-hype-around-3d-printing-it-fast, accessed March 30, 2015.
3. Venessa Wong, "A guide to all the food that's fit to 3D print (so far)," *Bloomberg Businessweek*, January 28, 2014, www.businessweek.com/articles/2014-01-28/all-the-food-thats-fit-to-3d-print-from-chocolates-to-pizza, accessed March 30, 2015.
4. Teresa F. Wegrzyn, Matt Golding, and Richard H. Archer, "Food layered manufacture: A new process for constructing solid foods," *Trends in Food Science & Technology*, October 2012, vol. 27, issue 2, pp. 66–72.
5. Jane Benson, "Chow from a 3-D printer? Natick researchers are working on It," *Army Technology Magazine,* July/August 2014, www.army.mil/article/130154/Chow_from_a_3_D_printer__Natick_researchers_are_working_on_it/, accessed March 30, 2015; Matthew Boyle, "Nestle aiming to develop Nespresso of nutrients," *BloombergBusiness*, June 23, 2014, www.bloomberg.com/news/articles/2014-06-22/nestle-aiming-to-develop-a-nespresso-of-nutrients, accessed March 30, 2015.
6. This framework is described in Mark Cotteleer and Jim Joyce, "3D opportunity: Additive manufacturing paths to performance, innovation, and growth," *Deloitte Review*, January 17, 2014, http://dupress.com/articles/dr14-3d-opportunity/?coll=8717.
7. See Mark Cotteleer, Jonathan Holdowsky, and Monika Mahto, *The 3D opportunity primer*, Deloitte University Press, March 6, 2014, http://dupress.com/articles/the-3d-opportunity-primer-the-basics-of-additive-manufacturing/?coll=8717.
8. See, for example, Liang Hao et al., "Material characterisation and process development for chocolate additive layer manufacturing," *Virtual and Physical Prototyping*, vol. 5, issue 2, June 16, 2010, pp. 57–64; and Daniel L. Cohen et al., *Hydrocolloid printing for customized food production*, Cornell University, August 2009, http://creativemachines.cornell.edu/sites/default/files/SFF09_Cohen1_0.pdf, accessed March 30, 2015.
9. Arianna Valentini and Ron Gilboa, "3D printing: Technologies, markets, and opportunities," InfoTrends, June 2013, *http://webobjects.cdw.com/webobjects/media/pdf/*3dprinting/InfoTrends.pdf, accessed March 30, 2015.
10. NASA, "3D printing: Food in space," May 23, 2013, www.nasa.gov/directorates/spacetech/home/feature_3d_food.html, accessed March 30, 2015.
11. Business Wire, "Hershey unveils world's first public 3-D chocolate candy printing exhibit," December 17, 2014, www.businesswire.com/multimedia/home/20141217005885/en/, accessed March 30, 2015.
12. Wong, "A guide to all the food that's fit to 3D print (so far)."
13. Brooke Kaelin, "Cornell students 3D print with food," *3D Printer World*, July 18, 2013, www.3dprinterworld.com/article/cornell-students-3d-print-with-food, accessed March 30, 2015.
14. Deborah Southerland, Peter Walters, and David Huson, *Edible 3D printing*, Society for Imaging Science and Technology, 2011, www.imaging.org/ist/publications/reporter/articles/REP26_5_6_NIP27DF11_SOUTHERLAND_PG819.pdf, accessed March 30, 2015.
15. Lidia Serenó et al., "A new application for food customization with additive manufacturing technologies," American Institute of Physics Conference Proceedings, April 30, 2012, vol. 1431 issue 1, pp. 825-833.
16. Southerland, *Edible 3D printing*.
17. Ibid.
18. Lauren Keating, "You can now print edible pizza with a 3D 'Foodini' printer," Tech Times, November 6, 2014, www.techtimes.com/articles/19630/20141106/startup-serves-up-edible-pizza-burgers-3d-foodini-printer.htm, accessed March 30, 2015.
19. For a deeper discussion of binder jetting, see Cotteleer, Holdowsky, and Mahto, *The 3D opportunity primer*.

20. Todd Grimm, *User's Guide to Rapid Prototyping* (Society of Manufacturing Engineers, 2004), p. 163.

21. Zak Stone, "Where sugar meets science: Silver Lake's sugar lab is using 3D printing to change the world of high-end cake design," *Los Angeles Magazine*, October 21, 2013, www.lamag.com/digestblog/sweet-science-silver-lakes-sugar-lab-takes-cake-to-a-new-level-with-3-d-printing/, accessed March 30, 2015.

22. Megan Willett, "This is the best 3D food printer we've seen yet—and it makes stunning desserts," *Business Insider*, September 12, 2014, www.businessinsider.com/3d-systems-chefjet-printers-2014-9, accessed March 30, 2015.

23. Southerland, *Edible 3D printing*.

24. Lori Zimmer, "FabCafe in Japan lets customers create 3D gummies of themselves," *Inhabit*, January 24, 2015, http://inhabitat.com/fabcafe-lets-you-3d-print-a-gummy-version-of-yourself/, accessed March 30, 2015.

25. For a full description of Deloitte's additive manufacturing framework, see Cotteleer and Joyce, "3D opportunity."

26. For a more complete discussion of tooling issues, including molding, see Mark Cotteleer, Mark Neier, and Jeff Crane, "*3D opportunity in tooling: Additive manufacturing shapes the future*," Deloitte University Press, April 7, 2014, http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-tooling/.

27. This isn't to say that such a thing cannot exist but, rather, that in the current state they appear to be rare indeed. We will be keeping watch to see what trends emerge over time.

28. NASA, "3D printing: Food in space."

29. Aarti Shahani, "Army eyes 3D printed food for soldiers," NPR, November 4, 2014, www.npr.org/blogs/alltech-considered/2014/11/04/361187352/army-eyes-3d-printed-food-for-soldiers, accessed March 30, 2015.

30. TE Edwards, "Barilla announces their 3D printed pasta contest winners," *3DPrint.com,* December 22, 2014, http://3dprint.com/32604/3d-printed-pasta-contest/, accessed March 30, 2015.

31. Wong, "A guide to all the food that's fit to 3D print (so far)."

32. Bonnie Burton, "Print out breakfast with a pancake printer," *CNET*, May 21, 2014, www.cnet.com/news/print-out-breakfast-with-a-pancake-printer/, accessed March 30, 2015. Kickstarter page: www.kickstarter.com/projects/1853707494/pancakebot-the-worlds-first-pancake-printer.

33. Michelle L. Terfansky, et al., "3D printing food for space missions," presented at AIAA Space 2013 Conference, September 2013, http://arc.aiaa.org/doi/abs/10.2514/6.2013-5346, accessed March 30, 2015.

34. Michael Molitch-Hou, "Nestle wants to meet dietary needs with 3D food printing," *Bloomberg*, June 24, 2014, www.3dprintingindustry.com/2014/06/24/nestle-wants-meet-dietary-needs-3d-food-printing/, accessed March 30, 2015.

35. Damien Pearse, "Transforming mealtimes with 3D-printed food," *Horizon: The EU Research & Innovation Magazine*, April 7, 2014, http://horizon-magazine.eu/article/transforming-mealtimes-3d-printed-food_en.html, accessed March 30, 2015.

36. Business Wire, "Hershey unveils world's first public 3D chocolate candy printing exhibit."

37. Kim van der Sangen, "First 3D food printer in Dutch supermarket Albert Heijn," 3DFoodPrinting.com, February 9, 2015, http://3dfoodprintingconference.com/food/first-3d-food-printer-dutch-supermarket-albert-heijn/, accessed March 30, 2015.

38. Genevieve Shaw Brown, "Vending machine customizes your Oreos lickety-split," *ABC News*, March 12, 2014, http://abcnews.go.com/blogs/lifestyle/2014/03/vending-machine-creates-customized-oreos/, accessed March 30, 2015.

39. Wong, "A guide to all the food that's fit to 3D print (so far)."

40. Jelmer Luimstra, "MELT Icepops: 3D printing an ice cream of your own face," 3DPrinting.com, January 21, 2014, http://3dprinting.com/news/melt-3d-print-ice-cream-face/, accessed March 30, 2015.

41. Brooke Kaelin, "3D printed baked goods made out of insects," *3D Printer World*, August 5, 2013, www.3dprinterworld.com/article/3d-printed-baked-goods-made-out-insects, accessed March 30, 2015.

42. US Department of Agriculture, "Frequently asked questions: Regulations, standards and guidelines," https://fsrio.nal.usda.gov/faq-page/regulations-standards-and-guidelines, accessed March 30, 2015.

43. Illinois Department of Public Health, "Food safety fact sheet: Critical temperatures for food service," www.idph.state.il.us/about/fdd/fdd_fs_foodservice.htm, accessed March 30, 2015.

44. Luis Rodriguez Alcalde, "Food printer, 3DigitalCooks," http://3digitalcooks.com/wp-content/uploads/2014/11/Final-Report_F3D.pdf, accessed March 30, 2015.

Contacts

Mark Cotteleer
Director
Deloitte Services LP
+1 414 977 2359
mcotteleer@deloitte.com

Kim Porter
Principal
Deloitte Consulting LLP
+1 312 486 4481
kporter@deloitte.com

Jim Joyce
Specialist leader
Deloitte Consulting LLP
+1 617 585 4869
jjoyce@deloitte.com

Acknowledgements

The authors would like to thank **Robert Libbey, Neelakantan Subramanian,** and **Aleem Ahmed Khan** for their research contributions to this report.

Follow @DU_Press

Sign up for Deloitte University Press updates at DUPress.com.

About Deloitte University Press

Deloitte University Press publishes original articles, reports and periodicals that provide insights for businesses, the public sector and NGOs. Our goal is to draw upon research and experience from throughout our professional services organization, and that of coauthors in academia and business, to advance the conversation on a broad spectrum of topics of interest to executives and government leaders.

Deloitte University Press is an imprint of Deloitte Development LLC.