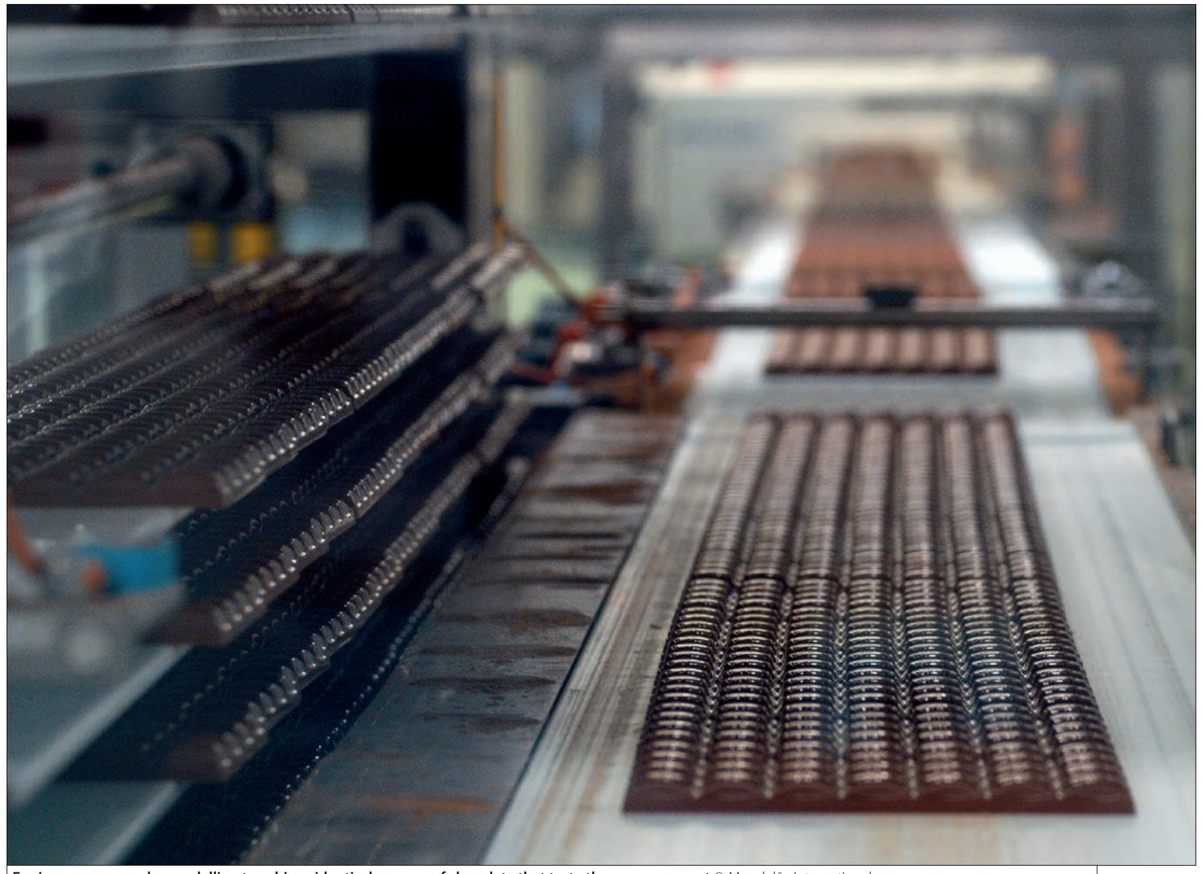


Engineers use complex modelling to achieve identical squares of chocolate that taste the way we expect © Mondelēz International

RAISING THE BAR

There are numerous engineering challenges involved in manufacturing chocolate to consistent standards of taste, texture and appearance. Neil Cumins investigated the engineering behind some of the UK's most popular confectionery.

Chocolate's place in popular culture needs no introduction, yet the engineering behind it is often overlooked. As we snap off a square of our favourite chocolate, we don't think about how the uniformity of each square has been achieved, or stop to consider the complexity involved in developing a new product line.

A team of experts from Mondelēz International, the owners of Cadbury, shed some light on the process. Based in the company's Research, Development and Quality (RDQ) division in Birmingham, they are responsible for maintaining quality and consistency across the Cadbury range of products, as well as developing new manufacturing processes and product lines. In recent years, the team has developed the world's first 3D chocolate printer, calculated the precise tolerances involved in chocolate production, and used crystal morphology to develop a chocolate bar with 30% less sugar.

Cadbury's cocoa beans come from six key areas: Ghana, Côte d'Ivoire, Indonesia, India, the Dominican Republic, and Brazil © Mondelēz International

THE BOURN' IDENTITY

Since the 19th century, the Cadbury brand has been synonymous with Bournville – a model village in Birmingham founded by the Cadbury family that contains a factory and hundreds of homes built for employees. Bournville remains one of the leading global bases for Mondelēz International's RDQ division, and it's here that a group of experts studies topics as diverse as fluid dynamics, structural mechanics, computational chemistry, and data science. Staff have been recruited from fields including food engineering and industrial design; mathematics and statistics; microbiology; and even psychology, reflecting the numerous technical processes involved in manufacturing chocolate.

Dr Beccy Smith is a Principal Scientist in the Modelling and Simulation team. Her department is responsible for developing digital tools that will help to develop better products more quickly, reducing costs: "We solve very diverse problems, from understanding the

A REAL MOUTHFUL

Chocolate manufacturing involves a number of highly technical processes, whose terminology explains their effects on the chocolate's material properties. For instance, tempering describes the process where cocoa butter is subjected to temperature-controlled crystallisation into one of six forms, known as polymorphs. The presence of tiny crystals in the chocolate can significantly affect its texture on the consumer's tongue, and crystal morphology describes the shape of the crystals present in solid chocolate. These can be used to replicate the taste and texture of a particular chocolate recipe with a different ratio of ingredients, such as a bar with a reduced sugar content.

Chocolate has to be viscous to be precisely moulded and shaped. However, as a shear-thinning fluid whose viscosity reduces when the fluid is mixed, keeping it consistently liquified is a particular challenge. The process of returning it to a solid state is known as crystallisation and is done in a carefully controlled manner once the chocolate has been poured into a mould that will determine its finished appearance.

impact of altering ingredients to improving consumer appreciation of our products." The department looks at problems such as predicting how moving to recyclable packaging could alter shelf life, and how process parameters can be optimised to improve quality.

Dr Smith cites a range of advanced scientific processes used at Bournville to develop a range of products from chocolates and biscuits to powdered beverages and meal components. "We use computational fluid dynamics (CFD) to predict the flow of liquids and gases and the transfer of heat. We conduct finite element analysis (FEA) to predict the movement and deformation of materials and transfer of heat. We undertake discrete event simulation to predict movement of material down a factory line or in a supply chain, alongside advanced process modelling to predict chemical and physical transformations within our factory unit operations."

Alongside data science techniques like artificial intelligence and machine learning, this scientific analysis directly influences the products we buy in shops, as Dr Smith explains: "The chocolate team often designs new shapes of filled chocolate units, such as caramels or cremes. These are made by filling a mould with liquid chocolate, then turning it over and vibrating it to shake out all but a shell of chocolate, before cooling to a solid and adding the filling and a chocolate base. Historically, we had to do many pilot plant experiments to find out what vibration settings create different thicknesses of shell, and many laboratory experiments to find out how strong the different shells are as we can't risk our products breaking in the supply chain." Now, by using computational modelling, the company can validate ideas on a computer instead, accelerating new product development.

"One question we got asked a lot was whether we'd done anything to the chocolate to be able to print on the machine. The answer was no. We used standard chocolate, and consumers were surprised that it tasted like standard Cadbury Dairy Milk, even though it was a bit flakier in terms of texture because of the layer by layer detail that you get from a 3D printer."

CHOCS AWAY

The RDQ team was also responsible for launching a 3D chocolate printer in 2019. This project started in 2015, with Senior Group Leader Nim Mistry heading the team from 2018, shortly after the decision was made to give the prototype machine its consumer debut in Australia. Nothing like this had been done before, and Nim's team recognised the need to demonstrate what could be achieved, while determining consumer demand for customised products and the public's enthusiasm for watching live chocolate printing.

"We had a year to launch, which was a tight timeframe," Nim recalls. "We had to run conceptual consumer tests on 3D printing, set up collaborations with partners to develop the concept, and then build the machine itself." This latter stage was handled by 3P Innovation, assembling a machine powered by standard 3D printing software: "The machine understands CNC G-code, which is similar to what you'd find in any other 3D printer software, and it also runs on the Rhino JavaScript engine. The main difference from a normal 3D printer is that we've got people working on the design with an understanding of how chocolate operates, to adapt the design to meet that criteria."

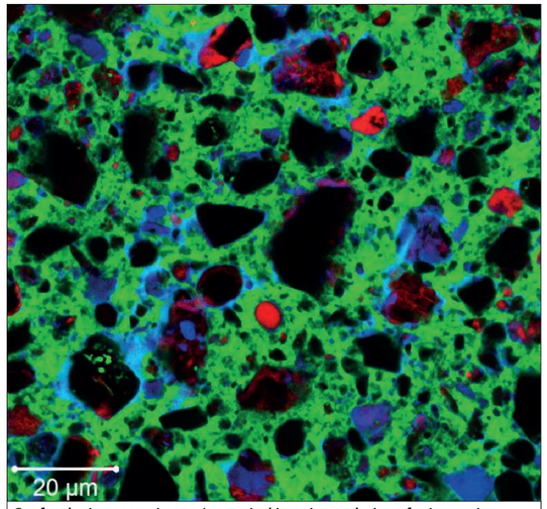
Standing two metres tall and 600 millimetres square, the printer was ready in time for World Chocolate Day 2019, and had a high-profile debut at Australian department store Myer. It produced eight identical chocolates at a time. Customers could select any one of 34 patterns, ranging from seasonal snowflakes and stars to Antipodean animals like turtles and kangaroos. The full alphabet was also programmed into the machine, which was Cadbury branded and equipped with a viewing window so people could watch the machine printing. "One thing that was important for a machine in a pop-up environment was that people could see it printing live," Nim points out.

The most vital attribute of the 3D printer was its ability to dispense chocolate without any deviation in taste, texture or consistency. Pending patents limit the RDQ team's ability to disclose how this was achieved, but Nim acknowledges the results have surprised many consumers: "One question we got asked a lot was whether we'd done anything to the chocolate to be able to print on the machine. The answer was no. We used standard chocolate, and consumers were surprised that it tasted like standard Cadbury Dairy Milk, even though it was a bit flakier in terms of texture because of the layer by layer detail that you get from a 3D printer."

AN ACQUIRED TASTE

It might come as a shock to British consumers, but chocolate recipes are often modified for different markets. Cadbury Dairy Milk in Australia tastes slightly different to its British sibling, in response to consumer preferences. However, it's critically important for every chocolate or bar produced in a specific country to deliver the consumer expectation of taste, texture and flavour. This is one of the areas Research Fellow Emma McLeod focuses on, and she acknowledges that customer expectations of quality standards impose stringent restrictions on product specifications.

The RDQ team uses cutting-edge technology to standardise the production process and the quality of its output, as Emma explains: "I currently lead a platform investigating how to bring more of these measurements online, so that we have real-time measurement of quality, rather than relying on infrequent sampling and after-the-event measurement. Once we have the online measurements, we can then enable better control of our processes using advanced control techniques. These quality standards are important as they ensure that we deliver our consumer promise on every bar, right first time." Ensuring that the systems work in real time requires a lot of design creativity.



Confocal microscopy image (an optical imaging technique for increasing optical resolution and contrast of a micrograph) showing the breakdown of ingredients in chocolate: fat (green), sugar (black), protein (red), and cocoa solids (blue) © Mondelēz International

SMOOTH OPERATOR

Taste and texture are critical to how consumers perceive chocolate. Ensuring that the notoriously tricky material remains completely smooth is a key quality parameter. "Consumers talk about chocolate being sandy or gritty if there are particles bigger than 30 to 40 µm," admits Emma. "However, if we go too fine, the chocolate can be seen as slimy. As a result, we refine our chocolate and measure the particle size distribution." This is a challenge, as the liquid chocolate is a suspension of particles in a fat continuous system. It has a high viscosity and engineers can't use the light-based methods that are used in other industries, as you can't see through the liquid chocolate. Handling liquid chocolate is a challenge in itself: "It is generally seen as a shear-thinning fluid, but the solids can sediment and the fat can start to crystallise." Keeping the molten chocolate moving and suitably warm is therefore essential while measuring its constituent elements, as well as helping to preserve its smoothness.

Smoothness was also a critical factor in developing a version of Cadbury Dairy Milk chocolate with 30% less sugar. Dr Ian Noble is a Senior RDQ Director and he explains how this ambitious target imposed several formulation and process engineering challenges. "During the product design phase, we had to produce the correct microstructure in the final product to deliver the correct sensory experience while also delivering the correct material transformations through each unit operation, from Cadbury's milk chocolate crumb through to the final packed bar. Removing such a large proportion of the solid phase of a product required extensive work to find appropriate replacement materials that don't impact the oral processing of the product. We had to replicate the texture, melt rate, aroma release, and ingredient dissolution to

Removing 30% of the sugar from a bar of chocolate meant extensive work to find appropriate replacement ingredients that didn't impact the taste or texture of the product © Mondelēz International

deliver the Cadbury Dairy Milk chocolate product experience, using crystal morphology and final crystallisation process to deliver the required product microstructure."

Described by Mondelēz International as "the most significant innovation in the brand's history", the reduced-sugar milk chocolate reflects the challenges of calculating how raw ingredients can combine to achieve certain outcomes. According to RDQ Director Richard Bardsley, insights into how ingredients are structured or blended together help to build a greater understanding of how those ingredients deliver different taste and texture attributes: "When we can characterise the ingredient functionality more precisely within the actual product, it enables us to consider which is the most appropriate recipe combination, and which will deliver the best overall consumer experience. Increasing the manufacturing precision and complexity does give more formulation options, but there is always then a trade-off to consider in terms of the ingredient cost versus fixed asset cost."

This cost effectiveness is being achieved partly through greater automation, which has been an evolving process ever since the Bournville factory opened. Indeed, it has mirrored several industrial revolutions common to other manufacturing sectors. "Initially it used very basic mechanical power", says Richard, "before following the assembly line philosophy with automated machines." More recently, new high output manufacturing lines have been introduced. In the last five years, a significant transformation has occurred and now the majority of the Mondelēz International brands are produced on these new lines. This has improved productivity across the whole business, not just in chocolate processing. "The speed of these lines now requires a much higher use of automation for both the control and quality monitoring purposes. Products are moving so fast along conveyors that it's almost invisible to the human eye."

Greater automation has transformed the manufacturing process © Mondelēz International

FOILED AGAIN

The production lines are a blur of activity nowadays thanks to greater automation, which has always gone hand-in-hand with new product development. "Cadbury's originally made drinking chocolate," Dr Noble points out, "then moved into making chocolate and the iconic Cadbury Dairy Milk. The journey has continued to this day as a fundamental part of our DNA. The wonderful diversity of food cultures around the world requires us to work closely with consumers to ensure that our products meet their expectations and taste buds, while also exploring heritage ingredients from around the world, including cacao pulp in our new CaPao products."

Next time you unwrap the foil from a newly-launched bar of chocolate, it's worth taking a moment to consider the years of research and development involved in bringing it to market.

BIOGRAPHIES

The following Mondelēz International staff had input into the article:

Dr Ian Noble is a Senior RDQ Director at Mondelēz International.

Dr Beccy Smith is a Principal Scientist in the Modelling and Simulation team.

Nim Mistry is a Senior Group Leader.

Emma McLeod is a Research Fellow.

Richard Bardsley is an RDQ Director.