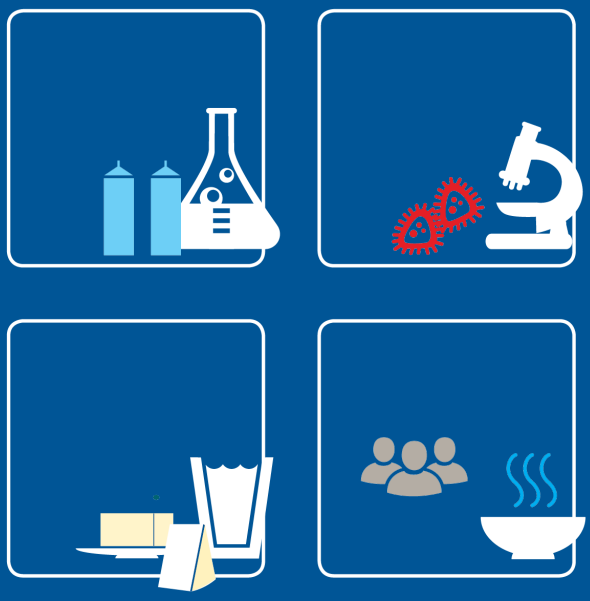
SLUTRAPPORT/FINAL REPORT
NR. 2023-179

Søren Balling Engelsen/Klavs Sørensen:

Big Cheese Data: Fuldautomatisk on-line 3D NIRS-målinger, modellering og styring af kvaliteten i osteproduktionen

Big Cheese Data: Fully automated on-line 3D NIRS measurements, modeling, and control of cheese production quality



Mejeribrugets
ForskningsFond

August 2023

Final report

for collaborative projects funded via the Danish Dairy Research Foundation (DDRF)

1. Title of the project

Danish:

Big Cheese Data: Fuldautomatisk on-line 3D NIRS-målinger, modellering og styring af kvaliteten i osteproduktionen

English:

Big Cheese Data: Fully automated on-line 3D NIRS measurements, modeling, and control of cheese production quality

Project nickname: "SayCheese"

2. Project manager

Klavs Martin Sørensen (retired from project in 2022)
Associate professor
University of Copenhagen
Department of Food Science
Chemometrics & Spectroscopy
Rolighedsvej 26
1958 Frederiksberg C
E-mail kms@food.ku.dk
Cell phone +45 21 69 59 08

From 2022:
Søren Balling Engelsen
Professor
University of Copenhagen
Department of Food Science
Food Analytics & Biotechnology
Rolighedsvej 26
1958 Frederiksberg C
E-mail se@food.ku.dk
Cell phone: +45 20 20 00 64
Phone: +45 35 33 29 53

3. Other project staff

Bjarke Damsgaard Jørgensen (retired from project)
Arla Foods Taulov Mejeri
Danbovej 2
7000 Fredericia

Kasper Damgaard (retired from project)
PhD Student
University of Copenhagen
Department of Food Science
Food Analytics & Biotechnology
Rolighedsvej 26
1958 Frederiksberg C

4. Sources of funding

Danish Dairy Research Foundation: DKK 1.984.000

GUDP (project QC-CREW): DKK 2.812.346

5. Project period

Project period with DDRF funding: January 2018 – December 2020

GUDP part of the project extended due to Corona to June 2022.

6. Project summary

Danish:

Mejeriindustrien i Danmark er berømt for sine oste. I 2022 producerede mejerierne 467.000 tons ost, hvoraf 88% blev eksporteret. Kvalitetskontrol er derfor af afgørende betydning og industrien vil gerne opgradere fra laboratorie-baseret at-line enkeltmålinger til 100 % on-line kvalitetskontrol af alle oste.

On-line kvalitetskontrol af osteproduktionen er imidlertid særdeles udfordrende pga. ostens størrelse og form og deraf følgende heterogenitet og kvalitetsgradienter i den enkelte ost. Nær-infrarød (NIR) spektroskopi har potentialet til at give et unikt kemisk-fysisk fingeraftryk af ostekvaliteten, og dette projekt vil undersøge mulighederne for at benytte rumligt opløst nær-infrarød spektroskopi til on-line kvalitetskontrol.

Dette projekt tager udgangspunkt i en metode, hvor en nær-infrarød spektroskopisk metode er optimeret og automatiseret til analyse af oste direkte i produktionen. Dette giver osteproducenten mulighed for at generere en meget stor database af målinger over forskellige oste, produktionsudsving, årstidsvariation, råvareudsving samt karakterisering af ostens udvikling under lagring. Databasen kan efterfølgende anvendes til at monitorere og karakterisere nye oste og beskrive deres forventede kvalitetsegenskaber efter endt lagring. Metoden er unik ved, at databasen udvikles organisk ved at tilføje alle nye målinger og vurderinger fra den løbende produktion af oste. Systemet får derved en selv-lærende egenskab og vil blive bedre og bedre til at forudsige kvaliteten af de færdige oste.

I dette projekt blev en fuldt fungerende robot for automatiske NIR-målinger af produktionsoste udviklet og installeret på Taulovs produktionslinje for gule oste. Projektet har opnået følgende:

(1) Konstruktion af robotsystem for rumligt distribuerede on-line NIR-målinger af produktionsoste.
(2) Gennemførelse af feasibility målinger at-line i laboratorie forsøg for den rumlige fordeling af indholdsstoffer (vand, fedt) i gule oste.
(3) Installation og test af robot i fuldskala produktionsmiljø hos Taulov for kvalitetskontrol af gule oste.

English:

The dairy industry in Denmark is famous for its cheeses. In 2022, the Danish dairies produced 467,000 tons of cheese, of which 88% was exported. Quality control is therefore crucial and the industry would like to upgrade from laboratory-based at-line single measurements to 100% on-line quality control of all cheeses.

On-line quality control of cheese production is, however, extremely challenging due to the cheese size and shape and consequently heterogeneity and quality-gradients within the cheeses. Near infrared spectroscopy has the potential to provide a unique chemical-physical fingerprints of cheese quality and this project explores the possibilities of using spatially resolved near infrared spectroscopy for on-line quality control.

This project is based on a method in which a near-infrared spectroscopic method is tailored and automated for cheese analysis directly in the cheese production. This allows the cheese producer to generate a very large database of measurements of different cheeses, production fluctuations, seasonal variation, commodity fluctuations and characterization of cheese development during storage. The database can subsequently be used to monitor and characterize new cheeses and describe their expected quality properties after storage. The proposed method is unique as the database is developed organically by continuously including all new measurements and assessments from the on-going cheese production. The system thus includes a self-learning capacity and will continuously improve its predictive capability of the quality of the finished cheese.

In this project, a fully functional robot for automatic NIR measurements of production cheeses was developed and installed on Taulov's production line for yellow cheeses. The project has achieved the following:

(1) Construction of robotic system for spatially distributed on-line NIR measurements of production cheeses.

(2) Carrying out feasibility measurements at-line in laboratory experiments for the spatial distribution of ingredients (water, fat) in yellow cheeses.

(3) Hygiene approval, installation, and test of robot in full-scale production environment at Taulov for quality control of yellow cheeses.

The cheese robot in action at Taulov Dairy.

7. Project aim

Danish:

Online kvalitetskontrol i osteproduktion er udfordrende pga. variationer i ostenes størrelse og form og deraf følgende heterogenitet og kvalitetsgradienter i en og samme ost. Nær-infrarød spektroskopi kan give et unikt kemisk-fysisk fingeraftryk af ostekvaliteten, og projektet skal undersøge muligheden for at bruge rumlig nær-infrarød spektroskopi til 100% online kvalitetskontrol.

Projektet baseres på en målerobot, der vha. en nær-infrarød spektroskopisk metode kan foretage rumlige målinger på de hele oste under selve produktionen. Projektet vil udvikle en metode, der ikke blot tillader måling på alle oste i et produktionsparti og for alle partier, men også kan beskrive variationen inde i den enkelte ost. Målingerne foretages uden, at der tages prøver ud af osten, direkte på osten mens den transporteres rundt på produktionslinjen. Der er altså tale om en komplet kortlægning af produktionskvaliteten, on-line, real-time og ikke destruktiv. Projektet vil vise hvilke essentielle kvalitetsparametre, fx kemisk sammensætning (fedt-, vand-, salt- og sukker-%, fedtsyresammensætning, proteinsammensætning, valleproteindel, pH), mineralsammensætning, sensoriske parametre (konsistens, lugt, smag, etc.), der kan bestemmes med metoden for hver enkelt ost. Alle disse parametre vil kunne bestemmes øjeblikkeligt efter endt måling af en ost, og derefter kommunikeres til mejeriets produktionsstyringssystem. Hvis en parameter i et produktionsparti afviger fra en ønsket norm, har mejeriet herefter mulighed for at udføre en korrigerende handling, og dermed bevare en høj produceret kvalitet.

Projektet udføres i samarbejde med Arla Foods Taulov Mejeri, der i projektet også får opbygget en vigtig videndatabase om de naturlige og procesrelaterede variationer i produkterne. Taulov producerer årligt 60.000 tons ost, og en igangværende forøgelse af produktionskapaciteten gør at behovet for on-line kvalitetskontrol bliver stadig mere aktuelt.

Projektet er unikt, da det er første gang, at der udføres 100% produktionskontrol. Endelig kortlægges variationer i produktionen – herunder variationer i råvaren som funktion af årstiden.

English:

On-line quality control of cheese production is extremely challenging due to the cheese size and shape and consequently heterogeneity and quality-gradients within the cheeses. Near infrared spectroscopy has the potential to provide a unique chemical-physical fingerprint of cheese quality and this project aim to explore the possibilities of using spatially resolved near infrared spectroscopy for 100% on-line quality control.

This project is based on a measurement robot in which a near-infrared spectroscopic method is tailored and automated for spatial cheese analysis directly in the cheese production. The project aims at developing a method that not only allows measurement on all cheeses in a production batch, but a method that also can describe the variation within the individual cheeses. The measurements are made without taking samples from the cheese, but rather directly on the cheese while it is being transported around the production line. This robot system thus contains a complete mapping of the production quality, on-line, real-time and non-destructive. The project aims to show which essential quality parameters, e.g., chemical composition (% fat, water, salt and sugar, fatty acid composition, protein composition, whey protein part, pH), mineral composition, sensory parameters (consistency, smell, taste etc) can be determined with the method. If successful all these parameters will be determined immediately after measuring a cheese, and then communicated to the dairy's production management system. If a parameter in a batch deviates from a desired norm, the dairy can carry out a corrective action, thus maintaining a high produced quality.

The project aims to install the cheese measuring robot at Arla Foods Taulov Dairy. Taulov Dairy produces 60,000 tons of cheese annually, and an ongoing increase in production capacity means that the need for on-line quality control is becoming increasingly relevant.

The project is unique in that it for the first time will allow 100% production control coverage of cheese production, and map variations in the produced cheeses and production derivations that may occur as a function to time of year, or variations in the supplied raw goods.

8. Background for the project

Currently, quality control during production of yellow cheese is done by manually sampling a single or very few cheeses in a production batch (cutting off a chunk). The extracted samples are sent to laboratory analysis, and the extraction partially destroy the cheese. The method has several shortcomings: the few sample points do not describe the intra-batch variation, and the simple extraction does not explain the intra-cheese variation. Additionally, the sample must be transported to the site laboratory and undergo manual processing, typically a Near-infrared spectroscopy (NIRS) measurement.

NIRS is a fast, nondestructive technique that provides multi-constituent analysis on virtually any matrix with levels of accuracy and precision that are comparable to primary reference methods. As another great benefit, NIRS analyses require no sample preparation or manipulation with hazardous chemicals, solvents, or reagents. The recorded NIR spectra contain a variety of chemical and physical information on the sample and its constituents.

In the food industry, NIRS analysis has been successfully implemented for a multitude of tasks for more than 25 years. Recently, attention has turned to analyzing solid and liquid chemical formulations for product quality monitoring of manufacturing operations. For raw material inspection, samples are scanned as received and the identity and quality of a material is confirmed, and as a during-process test and measurement tool, NIRS analysis provides reliable chemical information for control of food processes.

Thus, laboratory equipment capable of recording spectra of virtually any sample matrix is readily available from several commercial vendors (FOSS A/S, Denmark; Bruker GMBH, Germany; Q-Interline, Denmark). The dairy industry has found use of these laboratory instruments and is the go-to technology for bulk analysis (protein, fat, carbohydrates, water, salt etc.) of most dairy products. Since its introduction by FDA in 2004, the Process Analytical Technology (PAT) initiative has become a key utility for driving food production quality optimization. The food sector has benefited greatly from the PAT production paradigm as it is moving towards continuous flow processes that inherently can be difficult to control without direct observation and intervention during its progress. Essential for the PAT idea of continuous monitoring of 100% production quality control is the availability of data that can be used for decisions in the production process, and here, NIRS is recognized as being one of the most important technologies towards that goal. Several commercial solutions are available for NIRS analysis on-line and i-line in process streams of liquids or powders (optical dip- or process probes), but these can rarely be applied out-of-the-box on solids without use of specialized robotics or automation.

A state-of-the-art application of NIRS is the NITFOM Carcass Fat Quality Grading System produced by Carometec A/S, Denmark. The system is a hand-held NIRS device designed for probing the fat composition and process value of pork slaughter on a slaughterhouse conveyor – in full production speed. The system was developed by KU-FOOD and Carometec A/S in 2008 and has seen success in the pork slaughter industry. The system has been designed to operate under the difficult hygienic, operating and environmental conditions associated with a slaughterhouse. The system is commercially available and is helping abattoirs implementing PAT strategies on sorting and utilizing carcasses for optimal value creation. In addition, KU-FOOD has investigated an application of the NITFOM system to map the three-dimensional composition of fat on a slaughter carcass in a production context, showcasing the large potential of NIRS analysis in the food industry for understanding and describing production variations. The NITFOM principle has obvious applications for implementing PAT strategies in other food industries, a fact that is utilized in this project.

Traditionally, the thousands of data points in NIR spectral data are handled using classical chemometric methods such as PLS regression for quantification or PLS-DA for classification purposes, or in some cases, neural networks. Once calibrated, a model can predict constituents with high precision in similar sample matrices and within the calibration range of the model. Such models are typically sold by and maintained by the equipment vendor.

In a model of big data where it typically does not make sense to include all obtained data in the whole dataset due to significant differences in matrices variations or nonlinearities, local model systems have proven to be extremely effective. A local model is developed on the fly from a subset of data points in the big data cloud and can be used for automated PLS model calibration that leads to a superior prediction.

9. Sub-activities in the entire project period

The sub-activities of the project were divided up into 3 simple work packages and essentially conducted by Associate Professor Klavs Martin Sørensen with the help of Professor Søren B. Engelsen, MSc and PhD student Kasper Damgaard.

WP 1: PROTOTYPE

In WP 1 a prototype equipment, i.e., a sampling robot with an integrated NIR spectrometer was produced, that can be used for AT-line monitoring of the cheese production at the dairy:

WP 1.1 Design of system (robot, NIR spectrometer, sampling, data collection)

WP 1.2 Hygiene specifications (demands for installation in cheese production environment)

WP 1.3 Initial tests at KU

WP 2: CALIBRATION

An experimental plan is made that covers relevant variance in raw milk and production conditions for approx. 200 cheeses. This WP is designed to investigate the feasibility of the NIR robot for inter and intra cheese variations and to start developing calibrations for future on-line measurements.

WP 2.1 AT-line measurements at Taulov

WP 2.2. Reference measurements at KU

WP 2.3 Establishment of calibrations for bulk cheese parameters such as moisture, protein, and fat content

WP 3: ON-LINE IMPLEMENTATION

The method is assessed from a production perspective – is the method relevant in an online context?

WP 3.1 On-line installation of the robot at Taulov production line

WP 3.2 On-line testing of NIR robot at full production speed

10. Deviations

Big Cheese Data has been a typical corona project that has been delayed due to limited access to KU and extreme limited access to the Taulov production line. An extension of the project was applied for but not granted.

Nevertheless, the installation and demo-testing of the NIT robot was postponed multiple times and in the end the system was installed too late for proper testing (WP3). After initial and positive tests at the production line – the project ended, and we were not able to find new funding for a continuation of the project. Shortly after Klavs decided to leave academia.

11. Project results

The project results are best overviewed by going through the WPs:

WP 1: PROTOTYPE

We successfully produced a prototype equipment of the NIR robot and initial beta-testing were conducted at KU. Subsequently the robot was used for AT-line measurements at the dairy and here specifications were fine-tuned and agreed upon with respect to measurement speed, hygiene specifications and electronics.

WP 2: CALIBRATION

To calibrate the robot measurements a very thorough experimental plan was conducted at KU. The plan included approx. 200 cheeses with AT-line measurements at Taulov and reference measurements at KU. The experimental plan was made to cover the relevant variance in raw milk and production conditions. At KU the following measurements were performed: water content, pH, NaCl, NIR spectroscopy, ICP-OES, Fatty acid composition by GC-MS and exploratory ^{1}H-NMR. At Arla Taulov we performed simple sensorial analysis and standard QC analysis (FOSS). While this big experimental set-up was a part of three simultaneous MSc theses, the calibration work largely remain to be evaluated. We are currently writing up the conclusions of the exploratory investigation by NMR in a scientific paper. It shows interesting cheese metabolite changes between the cheeses based on lactic acid bacteria and those who also contain propionic bacteria. A new PhD student *Harshkumar Patel* will finalize the analysis.

WP 3: ON-LINE IMPLEMENTATION

A prototype equipment was built conforming to hygiene specifications from the dairy. However, to assess the robot from a production perspective, the robot was implemented and tested in the main production line of Denmark's largest cheese manufacturing facility at Taulov. This would have been a major achievement of any project. The robot was tested in full production speed and a video was made. However, due to corona and the additional security concerning the food production system, this achievement came too late in terms of funding and follow up of the equipment. The Big Cheese Data robot was finally dismantled at Taulov May 25th 2023. It was a sad day, but it will now take part in another Big Cheese Data project with Arla called EXCHEQUER.

12. The relevance of the results, including relevance for the dairy industry

While seriously hampered by Corona, BigCheeseData has introduced and prepared the Danish Dairy industry for Industry 4.0. At least we hope to have opened the eyes for the industry for the possible gains but also difficulties related to the integration and use of sensors and big data for enhancing the efficiency of production processes and the quality of the end products.

Knowledge of the state-of-the-art process combined with the production tools for proactive intervention and control, will limit the amount of manufacturing faults and the resulting scrap of valuable product. Especially within food production, new and resource effective production technologies have been pointed out as one of the cornerstones for competitiveness in the Danish food industry and process analytical technology with green measurement sensors such as the cheese robot may be one of our best routes to lower the environmental impact of food production.

13. Communication and knowledge sharing about the project

Papers in international journals:

K.M. Sørensen, F. van den Berg & S.B. Engelsen, NIR Data Exploration and Regression by Chemometrics—A Primer, In: Near-Infrared Spectroscopy. Theory, Spectral Analysis, Instrumentation, and Applications (Eds. Y. Ozaki, C. Huck, S. Tsuchikawa, S.B. Engelsen), Chapter 7, Springer, Singapore (2021), ISBN: 978-981-15-8647-7, pp. 127-189. (https://doi.org/10.1007/978-981-15-8648-4)

Popular Science papers:

Kasper Borg Damkjær, Klavs Martin Sørensen, Bjarke Damsgaard Jørgensen & Tove Kjær Beck. 20109. Fuldautomatisk on-line kontrol skal sikre ostekvaliteten. Mælkeritidende 2019(16). https://maelkeritidende.dk/sites/default/files/udgivelser/s._16_fra_mt_16_2019_hoej_oploes-2_0.pdf and https://maelkeritidende.dk/sites/default/files/udgivelser/fuldautomatisk_on-line_kontrol.pdf

Student theses:

MSc thesis: "Exploring the Application of VIS-NIR Spectroscopy and PTR-MS as Proxy Methods for Predicting Quality of Semi-hard Cheeses" by Anne Sofie J. Brund, Laura E. Ternstrøm and Signe K. Hylleberg. Department of Food Science, University of Copenhagen (2022).

Oral presentations:

Kasper Damgaard. "SayCheese! Upgrading the cheese quality control" International Conference on Near Infrared Spectroscopy, Australia, 15-20 September 2019.

14. Contribution to master and PhD education

Bachelor of Science (2022): Cæcilie Schade Cantby & Cæcilie Schade Cantby: Using Near Infrared Spectroscopy to Predict the Rheological Properties of Yellow Cheese A Feasibility Study

Bachelor of Science (2022), Line Lind Mogensen & Christina Stilund Drost: Brug af Nær-Infrarød Spektroskopi til Forudsigelse af Sensoriske Kvaliteter i gul ost

Master of Science (2022) Anne Sofie J. Brund, Supervisor: Klavs M. Sørensen

Master of Science (2022) Laura E. Ternstrøm, Supervisor: Klavs M. Sørensen

Master of Science (2022) Signe K. Hylleberg, Supervisor: Klavs M. Sørensen

New PhD student Harshkumar Patel (2022-2025). Supervisors: Klavs M. Sørensen & Søren B. Engelsen

15. New contacts/projects

The BigCheeseData project laid the foundation and contacts for the Innovation Fund Denmark supported project called Exchequer. This project concerns the development of PAT tools for the Mozzarella cheese production and the BigCheeseData robot will be tried to use for at-line rheology and NIR measurements.