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Søren Balling Engelsen:

REWARD – Bæredygtig anvendelse af procesvand

REWARD – Reuse of water in the food and bioprocessing industries

Mejeribrugets
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Final report

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1. Title of the project

REWARD – Reuse of water in the food and bioprocessing industries

REWARD – Bæredygtig anvendelse af procesvand

2. Project manager

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Arla Foods Ingredients (AFI, Denmark)

Novozymes A/S (NZ, Denmark)

Tetra Pak Filtration Solutions (formerly DSS Silkeborg A/S) (Denmark)

NIRAS (formerly Alectia A/S) (Denmark)

LiqTech International A/S (Denmark)

DHI Group (Denmark) terminated their participation in REWARD per 31.12.17 (internal restructuring of activities)

New partner per 01.01.2017: Wageningen University (WUR, The Netherlands); WU Operations Research and Logistics (partner Renzo Akkerman took on a position at WUR from TUM)

4. Sources of funding

Innovation Fund Denmark DKK 17.780.467,00

Danish Dairy Research Foundation DRF DKK 4.294.000,00

In-kind: DKK 4.111.502,00

5. Project period

January 2014-September 2018

6. Project summary

In Danish:

Ideen om, at vand udgør en uudtømmelig ressource, tilhører fortiden. Fødevare- og bioprocesserings-industrien er nogle af de største brugere og udledere af procesvand. Procesvand er en miljøbyrde, men er potentielt også en stor, uudnyttet ressource, idet procesvandet med fordel kan genbruges i produktionen. REWARD-projektet vil forsyne dansk fødevare- og bioprocesseringsindustri med grundlæggende teknologi og viden, som muliggør en langt mere effektiv udnyttelse af vand, og dermed bringer producenterne tættere på en 100 % bæredygtig produktion. REWARD anvender de effektive principper bag Process Analytical Technology (PAT) og Quality by Design (QbD) samt Hazard Analysis and Critical Control Points (HACCP) til at minimere forbruget af drikkevand og øge genbrug af proces- og rengøringsvand.

REWARDs mål er: (i) at udvikle og implementere nye højteknologiske sensorsystemer, der kan følge de kemiske og biologiske komponenter i procesvandstrømme og vandbehandlingens effektivitet samt (ii) at udvikle en helt ny fremgangsmåde til at optimere rensning af procesvand. Det er målet, at projektet placerer dansk videnskab, uddannelse og teknologi i det internationale førerfelt mht. udvikling og eksport af nye vandbesparende koncepter, ny vand-management-teknologi og uddannelse inden for optimering af vandudnyttelse og -kvalitet i forarbejdningsindustrien.

Projektet tager udgangspunkt i omvendt osmose-permeat fra en valleproces fra Danmark Protein A/S samt omvendt osmose-vand fra et typisk ostemejeri.

REWARD har etableret ny viden, der vil være med til at gøre dansk industri bæredygtig med hensyn til vandforbrug. Sikker genbrug af procesvand i fødevare- og biotekindustrierne starter med at etablere en effektiv analytisk, mikrobiologisk og statistisk platform, kombineret med en tilstrækkelig omfattende prøveudtagningsstrategi. REWARD har udviklet og testet denne platform!

Fremtidig genbrug af vand vil afhænge af en tæt overvågning og styring af procesvand. REWARD har ved brug af Proces Analytisk Teknologi og ”Design Space” opnået følgende:

- Udviklet og installeret et online real-time NIR spektroskopi-system til overvågning af procesvandstrømmene hos Arla Foods Ingredients.
- Opdaget en gærart, der tolererer barske omvendt osmose (RO) filterbetingelser.
- Udviklet et værktøj til forudsigelse af udfældning i filtersystemer.
- Undersøgt nye nanoteknologibaserede sensorsystemer til overvågning af vandkvaliteten.
- Udviklet et vandforsyningskæde-managementværktøj og brugt Arla Foods Taulov Mejeri som eksempel.

In English:

The idea that water is an inexhaustible resource belongs to the past. The food and bioprocessing industry are some of the largest users and processors of process water. Process water is an environmental burden, but is potentially also a large, unused resource, as the process water with advantage can be recycled to production. The REWARD project will supply the Danish food and bioprocessing industry with basic technology and knowledge, which enables a much more efficient utilization of water, and thus brings the producers closer to a 100% sustainable production. REWARD applies the effective principles behind Process Analytical Technology (PAT) and Quality by Design (QbD) as well as Hazard Analysis and Critical Control Points (HACCP) to minimize the consumption of drinking water and increase the recycling of process and cleaning water.

REWARD's objectives are: (i) to develop and implement new high-tech sensor systems that can monitor the chemical and biological components of process water flows and water treatment efficiency, and (ii) to develop a completely new approach to optimizing process water purification. The goal is for the project to place Danish science, education

and technology in the international leadership field in terms of development and export of new water-saving concepts, new water management technology and training in optimizing water utilization and quality in the processing industry.

REWARD has established knowledge necessary to bring the Danish industry closer to water self-sustainability. Safe process-water reuses in the food and biotech industries starts with an efficient, high-throughput analytical, microbial and statistical platform, combined with a sufficiently extensive sampling strategy, to 'map' the water household. REWARD developed and tested this platform!

Future reuse of water will depend on close monitoring and management of process water. Using Process Analytical Technology and Quality by Design technologies REWARD has:

- Developed and installed an on-line real-time NIR spectroscopy system for monitoring the water streams at Arla Foods Ingredients.
- Discovered a specie of yeast that was tolerant to harsh reverse osmosis (RO) filter conditions.
- Developed a tool for prediction of precipitation in filter systems.
- Investigated new nano-technology-based sensors for monitoring water quality.
- Developed a water supply chain tool and applied it to the Arla Foods Taulov Dairy.

7. Background for the project

In the dairy industry, huge amounts of water are turned over. The recyclability of these large amounts of water depends on the amount of the nutrients, they contain. The project aims to create an improved basis for sustainable reuse of process water in the dairy industry.

The project will investigate the possibilities for purification of process water from different dairy processes to a quality that enables the water to be used and treated as clean water equal with well water in production. The aim is partly (1) to develop sensors that can be used online for measuring small concentrations of ingredients in "relatively pure" RO permeate (ROP) and to pre-screen possible purification principles for use in industrial processes and partly (2) to analyze data from production facilities in order to create a multivariate modeling of variation and degree of purity in order to be able to design and control the purification process for to achieve the adequate purity. The project is based on whey RO permeate from Denmark Protein A/S and RO water from a typical cheese dairy.

Arla Foods' dairy production is currently (2014) producing more than 500,000 cubic meters of RO permeate annually in the form of whey (of which approx. 10% comes from Denmark Protein A/S) and a further approx. 1,000,000 cubic meters of condensate from evaporators, which today are led to treatment plants. If these enormous amounts of RO permeate and condensate could be purified to a quality close to clean water, it would provide a significant environmental and economic benefit. The RO permeate from Denmark Protein today has a small content of nutrients (50 mg COD), while the RO permeate from cheese dairies is somewhat higher (100-200 mg COD). However, both contents are so high that these permeate streams are handled internally in the production as milk and that, for example, the last rinse during a cleaning must always be done with fresh well water.

The aim of the project was to create an overview of the ingredients and their variation in the process water and to create the basis for a sustainable use of process water in the dairy industry. The studies are carried out with whey RO permeate from Denmark Protein and RO water from cheese production, as it is assessed that if these problems can be solved, then it is possible with a relatively modest effort to transfer the results to other RO permeate streams and condensate from dairy production in general.

The DDRF project reported here was a part of a Strategic Research Council (now Innovation Fund Denmark) project, REWARD, here focusing especially on the problems raised and described in the first two work packages (see below).

8. Sub-activities in the entire project period

	2015				2016				2017				2018			
Quarter	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Activities/milestones																
T1.1	X	X	M													
T1.2	X	X	X	X	X	M										
T1.3					X	X	X	M	X							
T1.4		X	X	X	X	M										
T1.5					X	X	X	X	X	X	M					
T1.6							X	X	M	X						
T2.1	M	X	X													
T2.2			X													
T3.1	X	X	X	X	M											
T3.2	X	X	X	X	M											
T3.3				X	X	X	X	X	M	X	X					
T4.1	X	X	M													
T4.2			X	X	X	M										
T4.3							X	X	X	M						
T5.1	X	X	X	M												
T5.2			X	X	X	M	X	X								
T5.3					X	X	X	X	M							
T6.1 & T6.2	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
T6.3		X		X		X		X		X		X	X		X	
T6.4	X				X				X				X		X	

WP1 – Real-time monitoring of water quality and equipment fouling

T1.1 Investigation and development of analytical methods for the characterization of RO permeate process water.

M1.1 An analytical platform for key reference analysis of EC&ROP and general process water in the food and biotech industry.

T1.2 Investigation (Phase I) and experimental design (Phase II) on production scale of EC&ROP process streams including on-line monitoring, incorporating the prototype sensors of WP2.

M1.2 Process understanding of RO permeate composition and flows/dynamics in the dairy and biotech industries.

T1.3 Evaluation of (industrial) pilot or full production scale of EC&ROP reuse optimization (Phase III).

M1.3 Industrial scale investigation of sustainable water used in the food industry.

T1.4 Investigation and development of analytical methods for the characterization of biofilm formation/surface contamination in food processes.

M1.4 An analytical platform for analysis of biofilm formation/surface contamination

T1.5 Investigation and experimental design on laboratory scale and industrial scale of biofilm formation/surface contamination, including the prototype sensors of WP3.

M1.5 Statistical process monitoring toolset of biofilm formation/surface contamination.

T1.6 Development of proactive control strategy for the prevention and elimination of biofilms and surface contamination based on on-line measurements.

M1.6 Strategy for monitoring biofilm formation/surface contamination in the food industry.

WP2 – New Sensors for Water Quality Monitoring

T2.1 Design and development of disposable multi-colorimetric sensor array chips.

M2.1 A prototype system available for testing in WP1, WP3 and WP4.

T2.2 Design and development of electrochemical micro-fluidic (bio)sensor arrays.

M2.2 A prototype system available for testing in WP1, WP3 and WP4.

WP3 – Microbial safety evaluation of process water
T3.1 Microbiological characterization of selected food/dairy and biotech process water streams and evaluation of the efficacy of water treatment.
M3.1 A review of water treatment options in the food industry from a microbiological view.
T3.2 Comparison of monitoring methods for evaluation of process performance and detection of microbial contamination.
M3.2 Selection of scenarios for source water quality, water treatment, on-line monitoring methods and water reuse for risk assessment studies.
T3.3 Microbiological risk assessment studies of use and re-use of process water for the selected scenarios in the dairy and related industries.
M3.3 Industrial cases of sustainable and safe water use in the food industry and final thesis.

WP4 - Design-space Modeling of Process and Cleaning Water
T4.1 Investigation and development of modeling methods for the description of RO permeate process water.
M4.1 An active modeling platform for process water in the food and bio-tech industry.
T4.2 Investigation (Phase I) and experimental design (Phase II) on production scale process streams including on-line monitoring, incorporating the prototype sensors of WP2.
M4.2 Process and cleaning water understanding of composition and flows/dynamics in the food/dairy and biotech industry.
T4.3 Evaluation on pilot and full production scale of reuse optimization (Phase III).
M4.3 Industrial scale investigation of sustainable water use in the food and biotech industry.

WP5 – Water Supply Chain Management in food and bioprocessing industry
T5.1 Investigation of present practice and future developments of water use in the food/dairy and biotech industries in Denmark and worldwide.
M5.1 Comprehensive knowledge on present practice, future requirements and desires and upcoming developments with regards to water use in industry.
T5.2 Investigation of water reuse possibilities in one or more exemplary case studies.
M5.2 Development of prototype decision support tools for management of water reuse.
T5.3 Investigation of impacts of water reuse potentials on energy use, waste water composition, waste water treatability and potential to reuse raw materials and by-products and how this affects the overall environmental management in case studies.
M5.3 Assessment of environmental impacts of water saving and water reuse options and integration of this into the prototype decision tools for management of water reuse.

WP6 - Project coordination and dissemination
T6.1 Establish the necessary network and infrastructure within the REWARD project.
T6.2 Ensure that REWARD WP meetings are being held (ad hoc, but no less than four a year) and that the project stays focused at reducing the water consumption.
T6.3 Ensure that results are effectively communicated within the project and that REWARD project meetings are being held (twice a year).
T6.4 Coordinate with the inSPIRe consortium (*inSPIRe ran out, much more coordination has been performed with the initiatives 'BIOPROII', 'Water Efficient Dairies' and in particular with 'DRIP' (INNO+ partnership).*

9. Deviations

Financial and timetable deviations compared to the initial expressions of interest to DDRF: REWARD was late fully staffed due to late appointments of PhD and postdoc scholarships, and therefore activities were limited the first year (2014). Later, re-budgeting was approved, prolonging the project with 6 months until 30 September 2018. In total, 14

REWARD meetings have been held with visits to all partners (a research community from Munich to Nr. Vium) and facilitated an increasingly efficient and multifaceted dialogue about the potentials and limitations of water reuse in the industry.

REWARD had no scientific deviations compared to the initial expressions of interest to DDRF.

10. Project results

Below is the final scientific reporting for the five scientific work packages (WP):

- WP1 – Real-time monitoring of water quality and equipment fouling (lead: KU FOOD)
- WP2 – New Sensors for Water Quality Monitoring (lead: DTU Nanotech)
- WP3 – Microbial safety evaluation of process water (lead: KU FOOD)
- WP4 - Design-space Modelling of Process and Cleaning Water (lead: DTU Chemical Engineering)
- WP5 – Water Supply Chain Management in food and bioprocessing industry (lead: WUR (until 31.12.2016, TUM))

WP1 – Real-time monitoring of water quality and equipment fouling (lead: KU FOOD)

Safe process-water reuses in the food and biotech starts with – or, should start with – a good, high-throughput analytical and statistical platform, combined with a sufficiently extensive sampling strategy, to 'map' the water household. REWARD developed and tested this platform!

RO and ROP processing water recovered in the food and dairy industry was the main focus of WP1. The streams were investigated by GC-MS (Gas chromatography–mass spectrometry) and ICP-OES (inductively coupled plasma - optical emission spectrometry) using different up-concentration and derivatization strategies and trace components were identified (Skou et al. 2018). Urea was identified as a main component, which is not retained in by the ROP and thus can serve as a performance indicator. A rapid NIRS (Near-infrared spectroscopy) method was developed. A full-scale production trial on urea dynamics showed stable concentration level, but with occasional spikes (Skou et al. 2017a). To follow this track, implementation of an online real-time NIRS system for monitoring the RO plant at Arla Foods Ingredients (AFI) has been installed incl. a spectrometer, five optical probes connected using a multiplexer, a complete database collecting unit with warning capabilities. It is still running at AFI collecting 1.5 million spectra every 6 months. The data is being aligned with other process data and will give a unique insight into the performance characteristics of the water processing system, and special events are matched in cooperation with AFI to train a statistical predictive model. The NIRS system including the spectral data base will be maintained and monitored for trend analysis at the double RO unit at AFI. Potential and limits for monitoring process water streams by NIRS is crystalizing out (Damkjær et al. 2019). Extreme Value Theory (EVT, a statistical modelling strategy to predict 'worse case scenarios') was applied as a process decision making tool, and as valuable tool in (water) management in the food and biotech industry (Skou et al. 2017b). Detailed, untargeted water sampling-schemes and analysis using ICP-OES and GC-MS (developed inside REWARD) is continued after REWARD and with REWARD partners in other industrial-academic partnerships.

Microbiological growth and survival potential in RO(P) systems in the dairy industry was investigated from a statistical perspective in close cooperation with WP3 (Stoica et al. 2017). Considerable yeast contaminations found on the permeate side of RO(P) elements after CIP have been mapped by alternative, less time-consuming analytical methods (Stoica et al 2018); the results will lead to a more cost-efficient large-surface quality control for the future. (Microbiological) surface fouling is a member of the 'unknown unknowns question' (trying to identify and quantify the presence of unfamiliar/new contaminants) that needs to be answered when monitoring water streams, and we investigated Wilks' ratio statistics in combination with fluorescence spectroscopy and tensor algebra to tackle this issue.

The Process Analytical Chemistry and Technology (PACT) inspired water sampling and analysis platform mentioned above is ready for use in existing and future research project and is an integral part of PACT teaching.

WP2 – New Sensors for Water Quality Monitoring (lead: DTU Nanotech)

The purpose was to develop and test new sensors for water quality monitoring/classification of water quality in process streams in the dairy industries, in collaboration with Arla foods ingredients (AFI).

Despite its effectiveness, hypochlorite is rarely used in CIP because of the potential formation of by-products formed by residual active chlorine species in the water potentially contaminating the product. AFI uses hypochlorite (P3-ansep CIP) as cleaning/disinfectant agent in only one of the process lines. Control of chlorine concentration is commonly done with a colorimetric method based on UV-Vis absorption spectrometry test using diethyl-p-phenylene diamine (DPD), which is somewhat toxic both before and after reaction with chlorine. Therefore, a new photometric method using a food compatible reagent, pyridoxamine – vitamin B6, to measure the presence of active chlorine in CIP water streams was developed. The method showed a linear correlation with the presence of active chlorine in water samples both using absorption spectrometry and with fluorescence spectrometry. Water samples taken at AFI during P3-ansep CIP at various times and water streams were tested for active chlorine content with the new method. Use of fluorescent measurements was better than absorption spectrometry due to matrix interference in the samples. The initial results indicated that the method can be used at-line to optimize water consumption during P3-ansep CIP, especially during the final washing steps.

A multi-colorimetric sensor system and chips were tested for the ability to classify different levels of water quality of permeate streams sampled after various purification steps. The sensor system is based on disposable multi-colorimetric sensor array chips consisting of an array of chemo-selective dyes, which changes color depending of the volatiles present in the headspace above a water sample. A portable prototype multi-colorimetric sensor system and chips (CrimeTracker) were used in the big water quality experiment. A total of 58 water samples were analyzed using the multi-colorimetric sensor system. The samples originated from three sources: process water from AFI (28 samples feed, permeate and retentate), commercial bottle water (19 samples), and tap water (nine samples). Each water sample was analyzed in triplicate and repeated over three weeks giving nine measurements in total per water sample. The objective was to assess the performance of the instrument to distinguish different process water streams collected at AFI and to compare these with commercial bottled water and tap water samples. However, based on the data analysis, the CrimeTracker was concluded to be unsuitable in measuring water quality due to limited reproducibility.

WP3 – Microbial safety evaluation of process water (lead: KU FOOD)

The microbiological investigations have served to determine the microbiological safety and quality of the product water from whey at different stages of the production. Although variations were found, the final product permeate at this production site was found to be satisfactory for a range of purposes thereby enabling water savings. Prolonged storage resulted in considerable growth and cannot be recommended. A new and surprising finding was the biofouling of some RO membranes with non-dairy associated yeast, which were very tolerant towards the cleaning and disinfection regimes used. These yeasts are filamentous and can cover large areas of the membranes but may be overlooked using traditional detection methods. Future activities should focus on establishing the source of this yeast, which may clog membranes and their removal.

Mapping of treated whey water found variations in the order of several log 10 colony forming units after ultrafiltration (UF), but consistently lower after RO and at levels below drinking water standards after a second RO. There was little correlation between levels and types of organisms found at the UF stage and after the final RO treatment. Although the nutrient level was low in the twice RO-treated water, some lactose and urea were present. Upon storage at temperatures ranging from 13 to 30 degrees, the population of naturally occurring microorganisms could grow to levels of 104 to 106 CFU/mL within weeks demonstrating that even the twice RO treated permeate should not be kept for longer periods in buffer tanks, if intended for use at the production site. The growth potential of several isolates from the treated water as well as several pathogens was examined. A range of gram-positive bacteria (representing *Lactobacillus*, and the pathogens *Listeria*, *Bacillus* and *Staphylococcus*) did not grow in the twice treated permeate while

several gram-negative isolates did (representing *Klebsiella* and *Acinetobacter* as well as the pathogen *Salmonella*). Also, urease negative isolates were capable of growing. Biofilm clogging the membranes were investigated and found to contain a large proportion of filamentous yeasts. Upon examination of more membranes, these yeasts were observed on a number of occasions, often covering large areas even after cleaning-in-place procedures. Since little information is known regarding these yeasts they were characterized more thoroughly and found to be tolerant to acid and alkaline treatments used in the industry as well as tolerant towards UV and moderate heating. Confocal microscopy also revealed that these yeasts seem to form the layer closest to the membranes. We hypothesize that these yeasts play a major role in biofilm formation in these environments as initiators and attachment background for bacteria helping the latter to protect themselves against the inactivation stresses encountered during cleaning and disinfection. We also showed that these yeasts may easily be overlooked due to their slow growth compared to the bacteria present and the lack of direct correlation between the CFU and their coverage due to both their aggregation (giving rise to fewer colonies) and their extensive coverage due to their size. The work on microbiological quality and safety has thus provided information on the quality and safety of the water in question, and the effect of different treatment stages and procedures. We have furthermore discovered new and potentially important organisms involved in biofouling and the characteristics of these. Last, but not least, we have been able to use this information both in the context of the Danish industry but also internationally in the efforts to support the shaping of new guidance papers by FAO/WHO and ultimately, Codex.

WP4 - Design-space Modelling of Process and Cleaning Water (lead: DTU Chemical Engineering)

The main result of this WP that can potentially lead to future water savings for the food and biotech industries is the development and implementation of a physicochemical modelling framework that can describe the dynamics of chemical equilibria and precipitation processes in water streams. The framework can potentially be used for simulation-based evaluation of scenarios to remove unwanted ions from a solution. The framework is experimentally validated, and can be used for mechanistic modelling of the design space, i.e. it can describe how different factors (e.g. temperature, addition of other ions) will influence the composition of a water sample, and whether or not specific concentration bounds/limits will be exceeded, e.g. to trigger precipitation. This approach can for example be used to predict the probability of occurrence of precipitation in water streams, in equipment used for treating water streams, etc.

The modelling framework has been published, and as part of our dissemination strategy it has been made available for free for potentially interested users. This is, we think, a way to reach out and increase the impact of our work within this WP.

During the project, an extensive series of lab-scale experiments has been performed with a number of Novozymes products, to investigate the potential implementation of RO at Novozymes in Kalundborg. The experiments were successful, meaning that the required concentration factors could be obtained with all samples tested. However, despite the positive lab-scale results, scaling up to pilot-scale RO implementation – originally scheduled to happen as part of the project – was finally delayed indefinitely due to industrial concerns about the high ion concentrations in the retentate produced as a side stream from the RO process, and about potential inhibition of the anaerobic processes in the industrial wastewater treatment plant as a consequence of the high ion concentrations.

For another case study (Arla), the potential for precipitating some of the ions in the retentate has been evaluated in the lab, and safe operating conditions for operating separation equipment without precipitation (design space) have been investigated with the physicochemical modelling framework. Potential measures that can be taken to reduce probability of occurrence of precipitation in membrane systems were evaluated using the physicochemical modelling framework. Experimental validation of these scenarios was tested at lab-scale: Sparging with CO2 led to a reduced pH and less precipitation. The addition of NaOH causes calcium precipitation and thus calcium could in principle be removed before the reverse osmosis step. However, the excessive cost of such an additional treatment, compared to current treatment cost, is a major drawback. Furthermore, the calcium free solution did not improve the flux through

the reverse osmosis membrane at laboratory scale, as other components seem to cause clogging of the membrane as well.

Ultrasonic irradiation was investigated to clean the reverse osmosis membrane. Laboratory-scale experiments showed significantly increased fluxes when ultra-sonication was applied in short cycles ex-situ. Further experiments are needed in the future as these tests were performed in a dead-end filtration mode, whereas cross flow filtration is applied at industrial scale. In addition, an in-situ operation would be preferred at large-scale.

WP5 – Water Supply Chain Management in food and bioprocessing industry (lead: WUR (until 31.12.2016, TUM))

WP5 focused on the production and supply chain management aspects of water reuse. The aim was to develop decision support tools to improve water reuse in the food and bioprocessing industries. The research resulted in several methods that can be used to integrate water reuse considerations in production planning and scheduling. Application of these methods show (1) how to balance water efficiency and production efficiency, (2) what the impact of water treatment technologies is, (3) how large the water saving potential can be for a specific dairy case study, (4) how real-time data can be used to improve the planning and control of production systems in food and bioprocessing industries, and (5) how to plan production and treatment capacities in the case multiple companies are collaboratively managing water resources.

The abovementioned results are mostly based on development of advanced planning methods building on mathematical programming approaches, in which water management is combined with production planning and scheduling. The first model that was developed (Pulluru and Akkerman, 2018a) lays the foundation for this work, and illustrates its use in evaluating the impact of water reuse and regeneration technologies. Secondly, we developed a water-integrated lot-sizing and scheduling approach for a multi-stage hybrid flow shop as found in cheese manufacturing systems (Pulluru et al., 2017; Pulluru and Akkerman 2018c). We combined continuous and discrete time grids to efficiently model production lots and water flows, as well as several practical considerations. Third, we developed a data-driven approach for water-integrated production scheduling that is capable of leveraging real-time data on the quantity and quality of water streams regenerated by treatment units (Pulluru and Akkerman, 2018b, Pulluru et al., 2018a). Fourth and finally, we developed a model for collaborative strategic water management across different firms, focusing on capacity planning under water scarcity (Pulluru et al., 2018b).

The research in this work package supports water management in industrial settings by providing methodologies that can be used to better match the supply and demand of water within and across factory walls. Case study results from a large cheese manufacturing plant indicate that improved balancing of water requirements over time can theoretically reduce water consumption by almost 90%, even though the increasing marginal costs of realization might become prohibitive. In general, the application of the methodologies developed in this research can support food and bioprocessing industries in achieving their water reuse targets, and it can help quantify the financial implications this might have.

Throughout the project, many students were involved in the work, writing their thesis on parts of the research. Most importantly, the research activities were primarily focused on 1 PhD thesis (Pulluru, 2019), which combines the abovementioned research in a thesis that is to be finished. Furthermore, 3 BSc theses, 9 MSc theses, and 1 interdisciplinary minor thesis were performed in support of the PhD research. This gave a significant number of student's insights in the modelling of water issues in production and supply chains, which has educated many engineers with an appreciation for sustainable production in the food and bioprocessing industry.

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

Research and innovation in water-saving technologies will have a major impact on the entire value chain: The price of water will increase in the future, and moreover, water is a limited resource. Focus on water consumption and a lesser

dependence on clean water will ensure and stabilize dairy production, ensure the environment better and further reduce production costs incl. both the cost of clean water and wastewater discharge. REWARD was a very timely project, which entered a period in which industrial interest in water reuse and water efficiency was continuously increasing. The two application industries involved in REWARD, Arla Foods Ingredients (AFI) and Novozymes, had very different water consumption characteristics and were at very different levels of water reuse from the beginning. However, they had in common that their ambitions with respect to water reuse were high, which guaranteed that the project stayed focused on reducing water consumption.

This project did form the basis for the actual design and optimization of purification processes for purification of RO permeate from various sources, which provided unprecedented opportunities for recycling process water as clean water in dairies. There was a large commercial saving associated with the project, as the large amounts of RO permeate and condensate before had to be led to treatment plants, where up to DKK 40 per cubic meter is paid in tax. With efficient recycling, the need to use clean water is further reduced. All in all, the effects of improved recycling of process water are more sustainable final products. The effects can be expected to be achieved as soon as measurement methods and techniques are implemented in the production, and can be followed up by comparing water consumption before and after implementation.

A main activity in REWARD has been the installation and operation of an online real-time NIRS system for monitoring an RO system at AFI. Five optical probes, a multiplexer, an OEM spectrometer, a database and a data transfer line now operate 24/7, collecting around 200,000 NIR spectra per month. The data analysis of this huge data flow is a gigantic challenge, but is expected to provide a unique insight into the performance of the RO plant. The potential and limitations of monitoring process water escapes with NIRS are beginning to crystallize out. In addition, a data-driven planning method based on online measurement development has been developed to illustrate how the collected data could be used to support real-time planning of water flows.

Research education:

Besides the formal education incl. specific courses for the PhD students involved in REWARD, the importance and economics of process water reuse and cleaning-in-place strategies have become a significant part of the KU MSc course 'Food Process Equipment' due to the REWARD initiative. Furthermore, a real example from REWARD is used in the 'BioPro World Talent Campus' (yearly one-week international PhD school) and the topic of water-integrated production scheduling was included in a TUM PhD course 'Advanced Planning in the Process Industry'. Finally, several BSc and MSc projects have emerged from REWARD.

12. Communication and knowledge sharing about the project

Papers in international journals:

C.B. Lyndgaard, M.A. Rasmussen, S.B. Engelsen, D. Thaysen, F.W.J. van den Berg, Moving from recipe-driven to measurement-based cleaning procedures: monitoring the Cleaning-In-Place process of whey filtration units by ultraviolet spectroscopy and chemometrics, Journal of Food Engineering (2014), 126:82–88

T.H.A. Berg, J.C. Knudsen, R. Ipsen, F.W.J. van den Berg, H.H. Holst, A. Tolkach, Investigation of consecutive fouling and cleaning cycles of ultrafiltration membranes used for whey processing, International Journal of Food Engineering (2014), 10:367-381

J.K. Jensen, N. Ottosen, S.B. Engelsen, F.W.J. van den Berg, Investigation of UF and MF Membrane Residual Fouling in Full Scale Dairy Production using FT-IR to Quantify Protein and Fat, International Journal of Food Engineering (2015), 11:1-15

J.K. Jensen, J.M.A. Rubio, S.B. Engelsen, F.W.J. van den Berg, Protein Residual Fouling identification on UF Membranes using ATR-FT-IR and multivariate curve resolution, Chemometrics and Intelligent Laboratory Systems (2015), 144:39-47

T.H.A. Berg, R. Ipsen, Niels Ottosen, A. Tolkach, F.W.J. van den Berg, Influence of reduced cleaning-in-place on aged membranes during ultrafiltration of whey, International Journal of Food Engineering (2015), 11:447-455

A. Klimkiewicz, A.E. Cervera-Padrell, F.W.J. van den Berg, Modeling of the Flux Decline in a Continuous Ultrafiltration System with Multiblock Partial Least Squares, Industrial & Engineering Chemistry Research (2016), 55:10690-10698

P.B. Skou, T.H.A. Berg, S.D. Aunsbjerg, D. Thaysen, M.A. Rasmussen, F.W.J. van den Berg, Monitoring Process-Water Quality Using Near Infrared Spectroscopy and Partial Least Squares Regression with Prediction Uncertainty Estimation, Applied Spectroscopy (2017a), 71:410-421

C.E. Eskildsen, F.W.J. van den Berg, S.B. Engelsen, Vibrational Spectroscopy in Food Processing, Encyclopedia of Spectroscopy and Spectrometry, 3rd edition (2017), 4:582-589

T.H.A. Berg, N. Ottosen, F.W.J. van den Berg, R. Ipsen, Inline UV-Vis spectroscopy to monitor and optimize Cleaning-In-Place (CIP) of whey filtration plants, LWT - Food Science and Technology (2017), 75:164-170

P. B. Skou, S.E. Holroyd, F.W.J. van den Berg, Tutorial – applying extreme value theory to characterize food processing systems, Journal of Chemometrics (2017b), e2896:1-12

L.G. Johnsen, P.B. Skou, B. Khakimov, R. Bro, Gas chromatography - mass spectrometry data processing made easy, Journal of Chromatography A (2017), 1503:57-64

I.M. Stoica, H. Babamoradi, F.W.J. van den Berg, A statistical strategy to assess cleaning level of surfaces using fluorescence spectroscopy and Wilks' ratio, Chemometrics and Intelligent Laboratory Systems (2017), 165:11-21

P.B. Skou, B. Khakimov, T. Hansen, S. Aunsbjerg, S. Knøchel, D. Thaysen, F.W.J. van den Berg, Chemical characterization by GC-MS and ICP-OES of membrane permeates from an industrial dairy ingredient production used as process water, Journal of Dairy Science (2018), 101:135–146

K.B. Damkjær, K.M. Sørensen, S.B. Engelsen, Investigating the feasibility of using near-infrared spectroscopy for inline monitoring of the salt content in industrial process water, Proceedings of the 18th International Conference on Near Infrared Spectroscopy (Eds. S.B. Engelsen, K.M. Sørensen and F. van den Berg), IM Publications Open, Chichester, (2019), 23-29

I. Udugama, K. Gernaey, J. Bryde-Jacobsen, F.W.J. van den Berg, S. Caño las Heras, A. Kizhedath, H. Feldman, S. Soheil Mansouri, BIOPRO World Talent Campus: A week of real-world challenge for biotechnology post-graduate students, Education for Chemical Engineers (2018), 25:1-8

B. Uthuppu, A. Heiskanen, D. Kofoed, J. Aamand, C. Jorgensen, M. Dufva, M.H. Jakobsen, Micro-flow-injection analysis (μFIA) immunoassay of herbicide residue 2,6-dichlorobenzamide - towards automated at-line monitoring using modular microfluidics, Analyst (2015), 140:1616-1623

I.M. Stoica, E. Vitzilaiou, H. Lyng Røder, M. Burmølle, D. Thaysen, S. Knøchel, F.W.J. van den Berg, Biofouling on RO-membranes used for water recovery in the dairy industry, Journal of Water Process Engineering (2018), 24:1-10

Vitzilaiou, I.M. Stoica, S. Knøchel, Microbial biofilm communities on Reverse Osmosis membranes in whey water processing before and after cleaning. Journal of Membrane Science (2019), 587:117174-117181

E. Vitzilaiou, S.D. Aunsbjerg, N.A. Mahyudin, S. Knøchel, Stress Tolerance of Yeasts Dominating Reverse Osmosis Membranes for Whey Water Treatment. Frontiers in Microbiology (2020), 11:816:1-8

X. Flores-Alsina, C. Kazadi-Mbamba, K. Solon, D. Vrecko, S. Tait, D.J. Batstone, U. Jeppsson, K.V. Gernaey, A plant-wide aqueous phase chemistry module describing pH variations and ion speciation/pairing in wastewater treatment process models, Water Research (2015), 85:255-265

X. Flores-Alsina, K. Solon, C. Kazadi-Mbamba, S. Tait, K.V. Gernaey, U. Jeppsson, D.J. Batstone, Modelling phosphorus (P), sulphur (S) and iron (Fe) interactions during the (dynamic) simulation of anaerobic digestion processes, Water Research (2016), 95:370-382

C. Kazadi-Mbamba, X. Flores-Alsina, D.J. Batstone, S. Tait, Validation of a plant-wide modelling approach with minerals precipitation in a full-scale WWTP, Water Research (2016), 100:169-183

S.S. Mansouri, I.A. Udugama, S. Cignitti, A. Mitic, X. Flores-Alsina, K.V. Gernaey, Resource recovery from bio-based production processes: a future necessity? Current Opinion in Chemical Engineering (2017), 18:1-9 (Review/opinion paper)

I.A. Udugama, S.S. Mansouri, A. Mitic, X. Flores-Alsina, K.V. Gernaey, Perspectives on resource recovery from bio-based production processes: from concept to implementation, Processes (2017), 5:48 (Review/opinion paper)

D. Puyol, X. Flores-Alsina, Y. Segura, R. Molina, B. Padrino, J.L.G. Fierro, K.V. Gernaey, J.A. Melero, F. Martinez, Exploring the effects of ZVI addition on resource recovery in the anaerobic digestion process, Chemical Engineering Journal (2018), 335:703-711

P. Bürger, X. Flores-Alsina, H. Arellano-Garcia, K.V. Gernaey, Improved prediction of phosphorus dynamics in biotechnological processes by considering precipitation and Polyphosphate formation: a case study on antibiotic production with Streptomyces coelicolor, Industrial and Engineering Chemistry Research (2018), 57:9740-9749

S.J. Pulluru, R. Akkerman, Water-integrated scheduling of batch process plants: Modelling approach and application in technology selection, European Journal of Operational Research (2018a), 269:227-243

Easily read papers:

F.W.J. van den Berg, H.H. Holst, S.B. Engelsen, Water reuse and saving in the food industry: A new frontier in food manufacturing, New Food (2014), 17:49-53

S. B. Engelsen, F. van den Berg, M.H. Jakobsen, S. Knøchel, K. Gernaey, R. Akkerman, Mejerier på vandvognen, Mælkeritidende (2015), 15-16:9-11

S. B. Engelsen, F. van den Berg, K.M. Sørensen, N. Viereck, Når hver en dråbe tæller, Mælkeritidende (2020), 12:18-19

Student theses:

P.B. Skou (2017), Process-water characterization and quality monitoring in the dairy industry – moving towards replacing potable water, PhD thesis, University of Copenhagen, December 15, 2017

I.M. Stoica (2018), Characterization of surface fouling and biofilm formation under water reuse scenarios in dairy and meat industry, PhD thesis, University of Copenhagen, September 25, 2018

S.J. Pulluru (2021), Water reuse in the process industries: A planning and scheduling perspective, PhD thesis, Technical University of Munich, in prep.

S. Knøchel, Material regarding use of permeates and water reuse has been incorporated in the course "Hygiene and Sanitation" at FOOD KU. One report (7.5 ECTS) on "Reuse of water in the dairy industry" has been elaborated and one trainee report on "Growth potential of different microorganisms in treated food process water destined for reuse" (2016)

KU FOOD student thesis projects:

S. Knøchel, A report (15 ECTS) titled: “Identification of isolates from dairy industry membrane surface and permeate water samples” has been elaborated as well as a trainee report titled: “Characterization of microbiota in process water” (2017)

K.M Sørensen and S.B. Engelsen have supervised a master thesis (30 ETCS) entitled: “Investigating the feasibility of using NIRS for inline monitoring of the salt content in industrial process water” by Kasper Borg Damkjær (2017)

S. Knøchel has supervised a master thesis titled: “Biofilm forming microorganisms from reverse osmosis membranes in dairy industry” by Eirini Vitzilaiou (2017)

S. Knøchel has supervised a report (15 ECTS) titled: “Evaluation of water reuse in the food industry” by Grethe Andersen

TUM Student thesis projects:

Ludwig Graf (BSc, TUM, 2014), Optimization of water reuse in the food industry

Christian Weiner (MSc, TUM, 2015), Water regeneration opportunities for batch processing industries

Dominik Ehl (BSc, TUM, 2016), Water-efficient supply chain planning in the food and bioprocessing industries

Malina Sikora (MSc, TUM, 2016), Water-efficient production scheduling in process industry: Comparative analysis of modeling approaches regarding computational effectiveness

Tobias Crönert (BSc, TUM, 2016), Optimizing water usage in a dairy plant: (Re-)scheduling in response to disturbances

Saion Chatterjee & Chetan Basuray (IDP, TUM, 2016), Water-integrated batch plant scheduler: An interdisciplinary project study

Ignacio Gonzalez Perez (MSc, TUM, 2017): Integrated production planning and water management in food industry

Maya Schwaninger (MSc, TUM, 2018): Data driven water management in food industry

Anne van der Heijden (MSc, WUR, 2018), Developing a framework to classify water quality for reuse in food industries

Matthias Aschenbrenner (MSc, TUM, 2018), Decomposition approaches for water-efficient production planning in food industries

Paloma Aparicio Escuder (MSc, TUM, 2018), Integrated capacity expansion and water management in process industries under competition for scarce water resources: A game theoretical modeling approach

Franziska Hanika (MSc, TUM, 2018), Strategic capacity planning under water scarcity: Effect of uncertainty

Johannes Spindler (MSc, TUM, 2018), Data-driven water management in food industries

Books, etc.

S.J. Pulluru, R. Akkerman, A. Hottenrott (2017), Integrated production planning and water management in the food industry: A cheese production case study. In: Computer Aided Chemical Engineering, 41:2677-2682

S.J. Pulluru, R. Akkerman (2018b), Data-driven water-efficient production scheduling in the food industry. In: Computer Aided Chemical Engineering, 43:1063-1068

Oral presentations at scientific conferences, symposiums etc.:

S.J. Pulluru, R. Akkerman (2016), Water reuse considerations in scheduling multipurpose batch plants: Modeling approach and analysis of regeneration options, Pre-prints of the Nineteenth International Working Seminar on Production Economics, February 22-26, 2016, Innsbruck, Austria, 12p

S.S. Mansouri, I.A. Udugama, A. Mitic, A. Rubin, L. Rudolfsson, K.V. Gernaey (2017), Reverse osmosis for water purification and reuse in the biotechnological industry: Process design, operation and economic guidelines. In: Antonio Espuña, Moisès Graells and Luis Puigjaner (Editors), Proceedings of the 27th European Symposium on Computer Aided Process Engineering – ESCAPE 27, October 1-5, 2017, Barcelona, Spain

Oral presentations at meetings:

F. van den Berg, From recipe-driven to measurement-based CIP, inSPIRe FOOD seminar on 'Membraner - optimering og besparelser i tid, vand og energi', April 9, 2014, Frederiksberg, Denmark

S.B. Engelsen, ”REWARD projektet”, talk at Partner meeting 'Det vandeffektive mejeri - på vejen mod det vandløse mejeri', June 23, 2014, Vejle, Danmark

R. Akkerman, Modelling water reuse in the food industry – Opportunities and Challenges, Third International Workshop on Food Supply Chains, November 4-7, 2014, San Francisco, USA (talk featured in SFSU Business Ethics Week 2014)

R. Akkerman, S.J. Pulluru, Integrating water reuse in operations management approaches for the food and bioprocessing industry, UQ-TUM Research Symposium on Water, Environment and Sustainability, June 11-12, 2015, Munich, Germany

S.J. Pulluru, R. Akkerman, Including regeneration possibilities to increase water reuse in scheduling multipurpose batch plants, EURO 2015, the conference of the European Association of Operational Research Societies, July 12-15, 2015, Glasgow, Scotland

S.B. Engelsen, The symphony of vibrations in NIR spectroscopy combined with chemometrics: a powerful cocktail, Tomas Hirschfeld Award Lecture, 17th International Conference on Near Infrared Spectroscopy, October 19, 2015, Foz do Iguassu, Brazil

R. Akkerman, S.J. Pulluru, Including regeneration possibilities to increase water reuse in scheduling multipurpose batch plants, INFORMS Annual Meeting, November 1-4, 2015, Philadelphia, USA

P.B. Skou, S.D. Aunsbjerg, S. Knøchel, F.v.d. Berg, Chemical and microbial characterization of reverse osmosis treated process water, Poster at Danish Water Forum, November 2015

REWARD was co-organizing a workshop on Water reuse in the dairy industry - Regulation, technology and control, February 29, 2016, Vejle, Denmark

S. Knøchel, participated in a workshop in a theme called “Show casing the Danish Water Sector”, May 15-18, 2016, Durban, South Africa

R. Akkerman, Sustainability in agri-food supply chain management: Opportunities and challenges, CYTED Network in Agro-BigData & DSS for Sustainable Development, October 6-7, 2016 (co-organized with CLAIO 2016, the Latin-Iberoamerican Conference on Operations Research), Santiago, Chile (keynote lecture)

R. Akkerman, S.J. Pulluru, Scheduling water reuse in the food industry: Theory and application, INFORMS Annual Meeting, November 13-16, 2016, Nashville, USA (invited session)

S. Knøchel, Water quality and efficiency in the food industry, the Water Science meeting, February 3, 2017, Copenhagen, Denmark

S. Knøchel, More milk and milk water – less tap and wastewater, the Dairy Research Congress (Mejeriforskningsdagen), March 1-2, 2017, Billund, Denmark

P.B. Skou, Chemical Characterisation and real-time quality monitoring of membrane permeates from an industrial dairy ingredient production, Flash talk at the Nordic Dairy Congress, June 7-9, 2017, Copenhagen, Denmark

R. Akkerman, Integrated production planning and water management: Theory and application to cheese production, Nordic Dairy Congress, June 7-9, 2017, Copenhagen, Denmark

K.B. Damkjær, Investigation of the feasibility for using NIRS for on-line monitoring of the mineral content and other impurities in reused industrial process water, ICNIRS, June 11-15, 2017, Copenhagen, Denmark

F.v.d. Berg, NIRS in process control … time is on my side, ICNIRS, June 11-15, 2017, Copenhagen, Denmark

P.B. Skou, Applying extreme value theory on Near Infrared Spectroscopy predictions of moisture content in milk powder, ICNIRS, June 11-15, 2017, Copenhagen, Denmark

S. Knøchel, HACCP and water use in the food industry, WHO/FAO expert meeting, June 2017, Bilthoven, NL

S.J. Pulluru, R. Akkerman, Water-integrated production scheduling in the food industry: A case study in cheese manufacturing, IFORS 2017 (21st Conference of the International Federation of Operational Research Societies), July 17-21, 2017, Quebec City, Canada

S.J. Pulluru, R. Akkerman, A. Hottenrott, Integrated production planning and water management in the food industry: A cheese production case study, 27th European Symposium on Computer Aided Process Engineering (ESCAPE 27), October 1-5, 2017, Barcelona, Spain

S.J. Pulluru, Integrated production planning and water management in the food industry: A cheese production case, Research Seminar, November 9, 2017, Wageningen University, The Netherlands

E. Vitzilaiou, S.D. Aunsbjerg, I.M. Stoica, S. Knøchel, Biofouling of membranes, Danish Microbiology Society Annual Congress, November 13, 2017 (Poster)

E. Vitzilaiou, S.D. Aunsbjerg, I.M. Stoica, S. Knøchel, Biofouling of membranes: filamentous yeasts - an overlooked factor?, Danish Water Forum, 12th Annual Water Research Conference, January 30, 2018, DTU, Lyngby, Denmark (Poster)

F.W.J. van den Berg, Process water in the food and beverage industry, Beverage Day, June 1, 2018, Copenhagen, Denmark

S.J. Pulluru, R. Akkerman, Data-driven water-efficient production scheduling in the food industry, 28th European Symposium on Computer Aided Process Engineering (ESCAPE 28), June 10-13, 2018, Graz, Austria

S.J. Pulluru, R. Akkerman, Strategic capacity planning in process industries under water scarcity, EURO 2018, the conference of the European Association of Operational Research Societies, July 8-11, 2018, Valencia, Spain

F.W.J. van den Berg, Reuse of water in the food and bio-processing industry, Indo-Danish collaborative workshop on Dairy, Food Ingredients and Water, September 6-7, 2018, Copenhagen, Denmark

REWARD project workshop "Water reuse in the food-processing industry" September 18, 2018 (25-30 participants), at the IWA World Water Congress and Exhibition, Tokyo, Japan, September 16-21, 2018.

Overview of workshop contents and contributions:
1. Welcome and introduction, R. Akkerman, Wageningen University, NL
2. Water reuse in the food-processing industry, S. Knøchel, University of Copenhagen, DK
3. Where do we come from (brief REWARD project background), K.M. Sørensen, University of Copenhagen, DK
4. On-line real-time monitoring of water quality, K.M. Sørensen, University of Copenhagen, DK
5. Design-space modelling of process and cleaning water, K.V. Gernaey, Technical University of Denmark, DK
6. Microbiological issues in a food safety context, S. Knøchel, University of Copenhagen, DK
7. Managing the logistics of water reuse, R. Akkerman, Wageningen University, NL
8. Discussion of opportunities and challenges

K.M. Sørensen, Reuse of quality water in the dairies based on "Big Cheese Data", Danmarks Mejeritekniske Selskab / Industry 4.0 - The future of manufacturing, October 11, 2018, Billund, Denmark

K.M. Sørensen, The need for real-time measurements in the coming circular water economy, IFC World Congress / Water Management & Sustainability, November 14-15, 2018, Herning, Denmark

K.M.S. Kaarsholm, E. Keliria, P. Mines, M. Antoniou, M.H. Jakobsen, H. R. Andersen, An alternative method to measure chlorine based on a food compatible chemical, Abstract submitted to 8th ICSPS, March 18-22, 2019, Marseille, France

Planned peer-reviewed articles:

S.D. Aunsbjerg et al., Isolation and characterization of microorganisms from RO treated dairy water, in prep.

S.J. Pulluru, R. Akkerman, Integrated production planning and water management in the food industry: A cheese production case study, in prep.

S.J. Pulluru, R. Akkerman, J. Spindler, Data-driven approach for water-integrated production scheduling in food industry, Computers & Chemical Engineering, in prep.

S.J. Pulluru, P.A. Escuder, R. Akkerman, Strategic capacity planning in process industries under water scarcity, in prep.

K.M. Sørensen, K.B. Damkjær, S.B. Engelsen, Monitoring of industrial RO water cleaning for recycling by NIR spectroscopy, Water Research, in prep.

13. Contribution to master and PhD education

PhD students:

WP1: Peter Bæk Skou, KU FOOD; Iuliana-Madalina Stoica, KU FOOD

WP3: Eirini Vitzilaiou, KU FOOD

WP5: Sai Jishna Pulluru, TUM School of Management

Postdocs:

WP1: Klavs Martin Sørensen, KU FOOD; Bekzod Khakimov, KU FOOD

WP2: Basil Uthuppu, DTU Nanotech; Paul D. Mines, DTU Nanotech

WP3: Stina Dissing Aunsbjerg, KU FOOD; Lukasz Krych, KU FOOD

WP4: Aleksandar Mitic, DTU Chemical Engineering; Xavier Flores-Alsina, DTU Chemical Engineering; Ines Pereira Rosinha, DTU Chemical Engineering; Pedram Ramin, DTU Chemical Engineering

14. New contacts/projects

Many project activities were running within and across the WPs. Several of the PhD students and postdocs involved in REWARD worked closely together, and in some cases WP leaders shared supervision formally (e.g. the collaboration between WP4/DTU Chemical Engineering and WP5/TUM, where Krist V. Gernaey was co-supervising the WP5/TUM PhD student on supply chain optimization supervised by Renzo Akkerman). WP1 was working in close cooperation with an industrial postdoc sponsored by Arla Foods Ingredients. Also, Renzo Akkerman became a participant in the TUM Water Cluster, an interdisciplinary research cluster within TUM.

Furthermore, REWARD has been collaborating closely with BIOPROII and the former inSPIRe platform and new progress was built and integrated with the results generated there. Also, REWARD arranged a workshop 29 February 2016 called ‘Water reuse in the dairy industry - Regulation, technology and control’ together with the related national projects: ‘Water Efficient Dairies’ and ‘DRIP’ (INNO+).

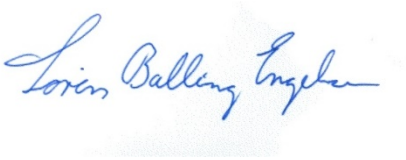
Regarding microbiological data and hazards, collaboration has been agreed between some of the partners within the projects DRIP (INNO+) and "Water efficient dairies" to create synergy.

Within the area of microbiological quality and safety, the project has resulted in collaboration with national stakeholders within the Danish Veterinary and Food Administration and DTU Food as well as DMRI/TI and technology providers such as UltraAqua. A collaboration on drip-flow biofilm has been performed with the Department of Biology, University of Copenhagen, leading to new possibilities within the field of microbial ecology. Internationally, the activities have resulted in an invitation (to WP3 leader Prof. Susanne Knøchel) to be member of a WHO/FAO expert panel on water reuse in order to support a new CODEX Alimentarius guidance. This activity may become instrumental in creating more flexible guidelines and regulations on a global scale in food industry water reuse. Meetings on potential future collaborations have been set up with Japanese researchers and there seems to be a growing international interest for the activities.

During the final stage of the project, WP5 leader Renzo Akkerman was asked to join the Advisory Board for the Carlsberg Young Scientists Community, with special focus on providing advice on sustainable supply chain management, amongst others dealing with reducing Carlsberg's water footprint. As such, the knowledge generated in REWARD continues to be used in other relevant (Danish) industrial contexts.

15. Signature and date

The project is formally finalised when the project manager and DDRF-representative (e.g. steering committee leader) have signed this final report.

Date: 18 February 2021, Signature, Project manager: 

Date: 18 February 2021, Signature, DDRF-representative: