H2020-SPIRE-2016
Grant n°723577

Deliverable 14

Public

D3.3
Technology combinations and selected scenario simulation in the dairy industry

April 2nd, 2019

Deliverable leader: CERTH

This project has received funding from the European Union's Horizon 2020 research and Innovation programme under grant agreement No 723577
October 2016 – March 2020 (42 month)

Summary

This report (Deliverable 3.3) presents work performed in the context of Task 3.2, where novel technologies are developed, for dealing with dairy industry effluents and wastewater, that would improve sustainability in the dairy processes. The objective of this report is to present the assessment of scenarios (i.e. novel technologies/systems for implementation in a dairy plant) aiming at minimizing freshwater use, reducing energy consumption for water and wastewater treatment and maximizing the recovery of valuable compounds. The reasoning behind these scenarios is outlined and the methodology as well as the results of the assessment are presented in this report. Supporting data, employed in this work, are reported in preceding Deliverables D2.4 ("Close loop recycling strategies and alternative water sources for the dairy industry") and D3.1 ("Design of the MBR pilot plant for the dairy industry").

Table of Contents

1. Glossary

BMC	Bare Module Cost
CA	Consortium Agreement
CAPEX	Capital Expenditure
CHP	Combined Heat and Power
CIP	Cleaning in Place
CW	Cleaning Water
COD	Chemical Oxygen Demand
DoW	Description of Work
EC	European Commission
EU	European Union
IEC	Installed Equipment Cost
MBR	Membrane bioreactor
OPEX	Operating Expenses
RO	Reverse Osmosis
TDS	Total Dissolved Solids
TIC	Total Capital Investment Cost
TOC	Total Organic Carbon
TS	Total solids
UF	Ultrafiltration
WP	Work Package
WWTP	Wastewater Water Treatment Plant

2. Contributions

No	Partners	Name
3	**MEVGAL**	Kostas GEORGAKIDIS
4	**PDC**	Evert VAN DER POL
12	**CERTH**	Anastasios KARABELAS, Dimitris SIOUTOPOULOS

3. Introduction

Work package (WP) 3 of the SpotView project deals with the development and assessment of technologies in simulated or operational environment, in three industrial sectors: Dairy, Steel, Pulp and Paper. In particular, Task 3.2 aims at developing strategy for sustainable reuse of process and cooling water in the dairy industry. Based on the outcomes of WP2, a favourable combination of the examined technologies is pursued for subsequent demonstration in the dairy industry. Various scenarios are developed by the Centre for Research and Technology-Hellas (CERTH) and assessed in parallel with Makedoniki Viomihania Galaktos Anonimos eteria (MEVGAL), aiming at minimizing freshwater consumption, reducing energy expenses for water and wastewater treatment and maximizing recovery of valuable compounds. Process Design Center (PDC) is collaborating in the assessment of technology combinations for the dairy industry by focussing on an optimized integration of technologies. A favourable scenario is the outcome of this analysis to be further examined through demonstration pilot facilities to be operated in the MEVGAL plant in WP4.

In the context of the aforementioned work plan, this deliverable, entitled *"Technology combinations and selected scenario simulation in the dairy industry",* aims at assessing the proposed scenarios.

3.1. Objectives

The main objective of the work presented in this deliverable is to assess the proposed processing scenarios that are aiming at minimizing freshwater use, reducing energy consumption for water and wastewater treatment and maximizing recovery of valuable compounds.

4. MEVGAL Dairy Plant

4.1. Present condition- Base case

MEVGAL is a major Greek dairy products company, located in Northern Greece. In the MEVGAL plant, mainly fresh cow milk is processed leading to dairy products that include yogurt, cheese and dairy-based deserts. In 2016, approximately 250 tons/day of milk were processed and roughly 2,000 m^3/day of fresh water from near-by wells were used. In general, dairy industry plants use water mainly for equipment cleaning and sanitation in order to maintain high hygiene standards [1,2]. Other major operations where water is needed are heating and cooling of process streams [3,4].

A comprehensive diagram of the current water flow distribution in the MEVGAL plant, is presented in **Figure 4.1,** whereas the main-stream identification (ID number) and respective water flow data are summarized in **Table 4.1**.

The following observations are made regarding major process units and areas of water consumption and treatment as well as related major effluent and process by-products streams.

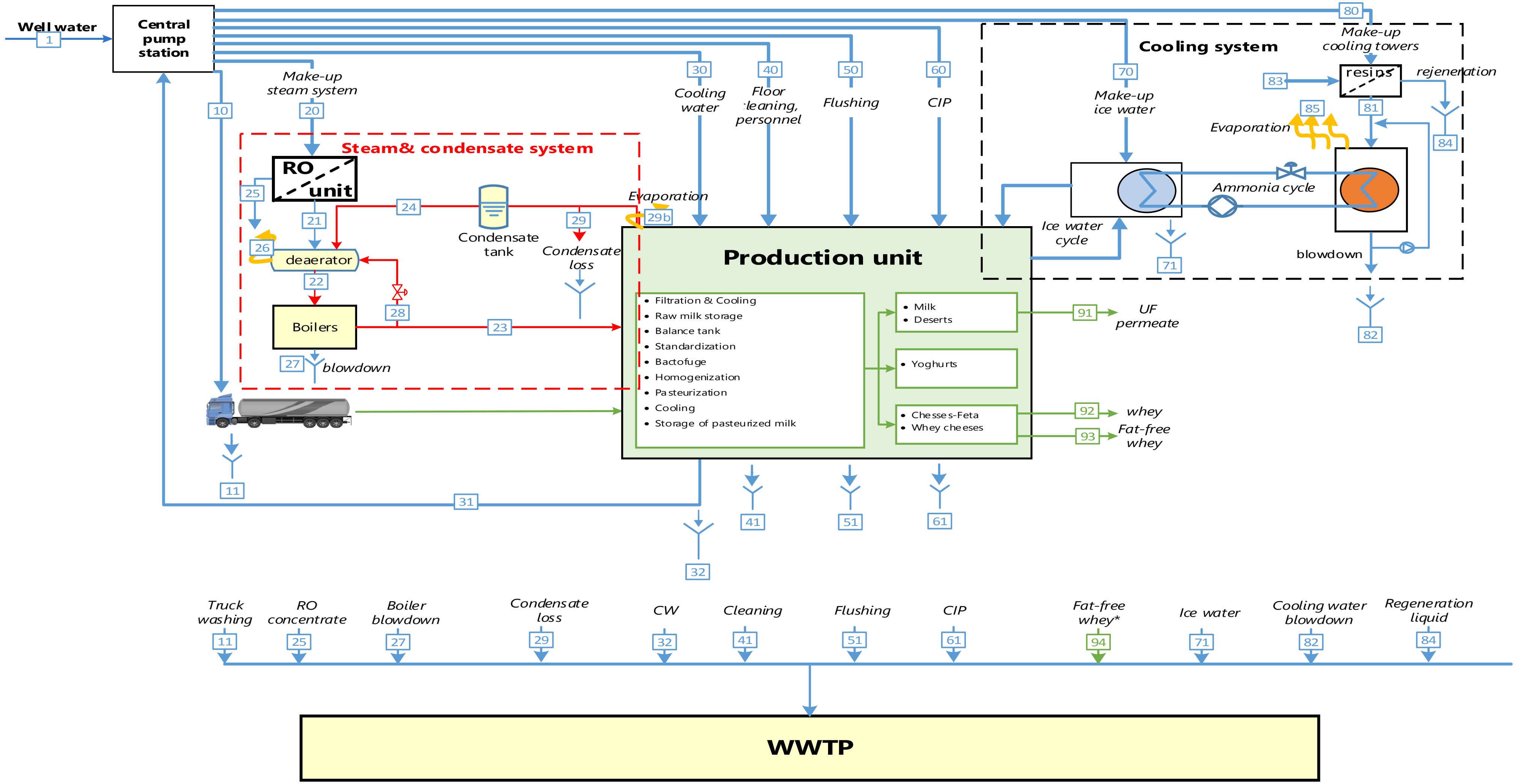

Figure 4.1. Comprehensive water flow diagram of MEVGAL dairy plant

Table 4.1. Identification of main streams (stream ID #) and corresponding flow rates of the MEVGAL dairy plant (Figure 4.1)

Feed water

stream ID	**1**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**		
Flow (m^3/day)	2205	30	65	1000	160	40	900	0	960		3155	2205

Wastewater

stream ID	**11**	**25**	**27**	**29**	**32**	**41**	**51**	**61**	**71**	**82**	**84**	**94**	**Total**
Flow (m^3/day)	30	6.5	1.9	50	50	160	40	900	0	480	2	4.5	1724.9

Steam system

stream ID	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**29b**
Flow (m^3/day)	58.5	95.1	92.7	37	6.5	0.9	1.9	0.5	50	5.7

Cooling system

stream ID	**81**	**82**	**83**	**84**
Flow (m^3/day)	960	480	2	2

By-products

stream ID	**91**	**92**	**93**
Flow (m^3/day)	7	16	18

Evaporation streams

stream ID	**26**	**29b**	**85**
Flow (m^3/day)	0.9	5.7	480

In general, one observes that a large number of wastewater streams ends up in the wastewater treatment plant, including:

- Cleaning in Place (CIP) streams [stream #61]
- Floor cleaning streams [#41]
- Equipment flushing streams [#51]
- Boiler [#27] and cooling tower blow-down [#82] streams.
- Reverse Osmosis (RO) concentrate [stream #25]
- Condensate loss [#29]
- Truck washing streams [#11]
- Resin regeneration liquid [#84]

Major by-product streams include:

- Ultrafiltration (UF) membrane permeate (from milk concentration); stream #91
- Whey; stream #92
- A portion of the fat-free whey (a by-product of "feta" cheese production); stream #93.

The aforementioned wastewater streams may be divided into two categories based on their *organic content*:

a) CIP streams, RO concentrate, floor cleaning streams, blow-down of cooling towers and boiler, truck washing streams, are characterized by a quite low level of organic load (TOC< ~10mg/L); thus, they are not considered for the recovery of valuable substances.

b) Flushing streams as well as whey, fat-free whey and UF permeate are streams of relatively high organic load.

It should be pointed out that the estimates of effluent rates depicted in Table 4.1 exhibit very significant variability, which is mainly due to the batch operations characterizing the dairy industry that lead to substantial fluctuation in daily water consumption and effluent stream rates. Therefore, the daily flow rates depicted in Table 4.1 are average values based on the water and effluent balances made on an annual basis. Nevertheless, the relative magnitudes of the major streams are fairly well established, and are summarized as follows:

- Various CIP streams are approximately 52% of the total wastewaters and together with the blowdown from the cooling towers (~28%) account for roughly 80% of MEVGAL wastewater streams that end up in the wastewater treatment plant (WWTP).
- The rest, comprising low organic load streams, account for the remaining ~20%.
- By-products streams (UF permeate, whey and fat-free whey) are roughly 2 % of the effluents, characterized by high organic load (TOC>10,000 mg/L).

Figure 4.2 presents, in pie-chart form, the distribution of effluent streams of the MEVGAL dairy plant in terms of volumetric flow rates. Upon inspection of this figure, the following conclusions can be drawn:

- *CIP effluents* comprising the largest wastewater stream (approx. 52% of the total) and *cooling-tower water blowdown* (representing ~27% of the wastewater streams) should be considered in the scenarios for water reuse due to their large volume.
- *By-product streams* (UF permeate, whey, fat-free whey) and *flushing streams* are roughly 4 % of the total effluents by volume. However, due to their high organic loading, they deserve consideration for either useful compounds recovery or energy production through anaerobic digestion.

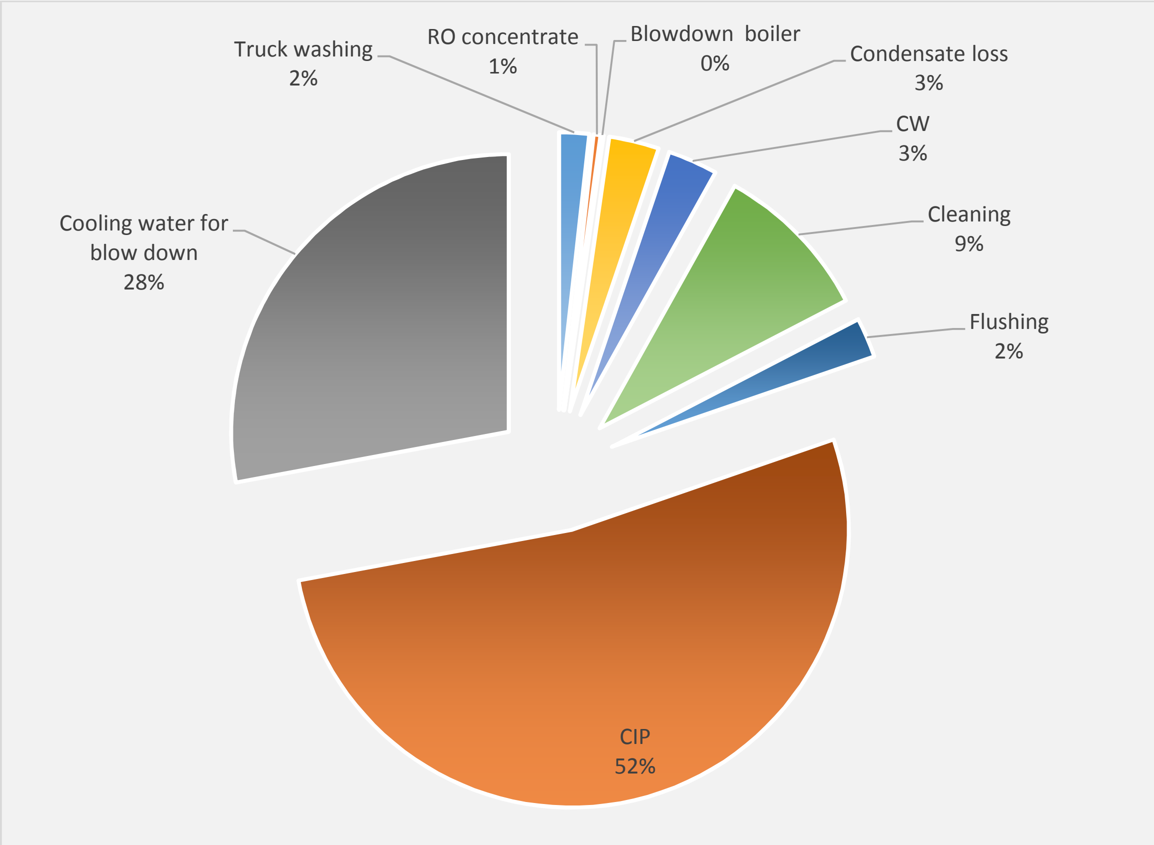

Figure 4.2. Distribution of volumetric flows from effluent streams in MEVGAL dairy plant

4.2. Characterization of plant feed-water and effluent streams

In order to decide on the development and assessment of the most favourable scenarios aiming at reduced fresh-water consumption, energy expenses and wastewater disposal, it is necessary to determine the characteristics of the water and wastewater/effluent streams. Therefore, a series of samples were obtained and the most important parameters of interest were determined at both CERTH and MEVGAL laboratories. In the following Tables 4.2-4, the typical characteristics of plant feed-water and of wastewater/effluent streams are summarized.

The plant feed-water (**Table 4.2**) pumped-out from neighbouring wells, is characterized by moderate salinity and conductivity, for this type of local ground water. Its composition serves as a reference for the ensuing assessment of treated effluent streams to be recycled.

The dominant characteristic of the by-product streams (**Table 4.3**) is the high concentration of *organic matter*, with Chemical Oxygen Demand (COD) in the range 60 to 90 g/L as well as of total Nitrogen (for the whey-containing *streams), that renders it appropriate for biological treatment.*

Table 4.2. MEVGAL plant feed-water (well water) characterization

	Parameters		Units	Sample 1st	Sample 2st	Mean Values
1	Calcium	Ca^{2+}	mg/L	79.0	83.2	81.1
2	Magnesium	Mg^{2+}	mg/L	31.8	60	45.9
3	Potassium	K^{+}	mg/L	3.0	3.7	3.4
4	Sodium	Na^{2+}	mg/L	51.8	60	55.9
5	Nitrate	NO_3^-	mg/L	31.0	68	49.5
6	Chloride	Cl^-	mg/L	97.6	177	137.3
7	Carbonate	HCO_3^-	mg/L	323	348	335.5
8	Sulphate	SO_4^{2-}	mg/L	N.D.	40.4	40.4
9	pH			8.1	7.84	7.97
10	Conductivity		μS/cm	754	1213	983.5
11	Total Dissolved	TDS	mg/L	483	816	649.5
12	Total hardness		mg/L $CaCO_3$	327	424	376
13	Total alkalinity		mg/L $CaCO_3$	265	285	275
14	Total organic carbon	TOC	mg/L	-	0.05	0.05

Table 4.3. Characteristics of high organic load effluent streams; i.e., whey, fat free whey, UF membrane permeate

	Parameters		Units	Whey	Fat-free whey	UF permeate
1	Fat		%	0.31	0.00	–
2	Proteins		%	1.13	0.46	–
3	Lactose		%	4.88	4.40	5.73
4	Total Solids	TS	%	7.92	6.44	–
5	Total Organic Carbon	TOC	mg/L	23,650	32,980	26,540
6	Chemical Oxygen Demand	COD	mg/L	90,000	70,200	57,600
7	Biological Oxygen Demand	BOD	mg/L	54,000	40,000	
8	pH		-	6.4	6.3	6.5
9	Conductivity		μS/cm	12,570	12,230	5,320

10	Turbidity		NTU	670	700	1.7
11	Total Phosphorus	TP	mg/L	480	330	-
12	Total Nitrogen	TN	mg/L	2,030	1,010	50
13	Colour		units	–	–	32.5
14	Total Dissolved Solids	TDS	mg/L	–	–	61,400
15	Total Suspended Solids	TSS	mg/L	6,500	3,160	22
16	Chloride		mg/L	4,850	3,990	1213

Water blowdown from the cooling towers are streams of interest to be considered for reuse, due to their relatively large total flow rate (approx. 480 m^3/day). The cooling towers are installed in several plant locations and the particular blowdown streams are directed to the WWTP. To evaluate the quality of these water blowdown streams, samples were obtained from different locations to estimate the parameters of interest, whereas indicative mean values were also determined. In **Table 4.4** these water blowdown characteristics are listed, showing significant variability between samples. Considering that the make-up water in the cooling towers is *deionized* (passing through a bank of ion-exchange resin beds), to remove scale-forming ions, the low concentration of such ions (e.g. Ca^{2+}, Mg^{2+}), and the corresponding increased concentration of potassium ions, are expected. Yet, the level of these concentrations is relatively low, even compared to the plant feed-stream (Table 4.2), so that the blow-down effluent is considered for reuse.

Table 4.4. Characterization of cooling tower effluent (blow down) streams

Parameters			Units	Sample 1^{st}	Sample 2^{nd}	Sample 3^{rd}	Average Values
1	Calcium	Ca^{2+}	mg/L	6.87	3.90	10.70	7.15
2	Magnesium	Mg^{2+}	mg/L	11.8	2.45	23.2	12.5
3	Potassium	K^{+}	mg/L	4.22	1.51	9.16	4.96
4	Sodium	Na^{2+}	mg/L	322	305	585	404
5	Nitrate	NO_3^{-}	mg/L	97	84	189	123
6	Chloride	Cl^{-}	mg/L	262	242	530	344
7	Carbonate	HCO_3^{-}	mg/L	476	433	802	570
8	Sulphate	SO_4^{2-}	mg/L	44.5	38.9	89.6	57.7
9		pH		8.72	8.73	8.99	8.81
10	Conductivity		μS/cm	1725	1556	2990	2090
11	Total Dissolved Solids	TDS	mg/L	1080	776	1840	1232
12	Total hardness		mg/L $CaCO_3$	52	6	96	51
13	Total alkalinity		mg/L $CaCO_3$	390	355	658	468

14	Total organic carbon	TOC	mg/L	0.29	0.87	0.81	0.65

4.3. Development of Scenarios – Preliminary assessment of streams

A preliminary overall assessment of the main streams of interest was made to develop candidate scenarios, to be subsequently assessed more systematically. On the basis of the foregoing data, the prime considerations that led to candidate scenarios are as follows:

i) Maximization of treated effluent recycling and of energy production.

The *combined maximization of treated effluent recycling and of energy production* was given priority, considering the high organic load of by-product streams (#91-93) and the rather high potential for biogas production if these streams were adequately diluted with other high volume mixed-effluent streams, such as those currently directed to the WWTP. The total stream directed to WWTP is characterized by modest variations in composition due to mixing of a variety of particular streams.

The *direct dilution of by-products with CIP streams was not considered* because of the increased concentration of alternating high and low pH of particular streams, which result from the implementation of CIP protocols intermittently in various locations of the plant. Similarly, *the direct dilution of by-products with blow-down* streams was not considered, since the latter could be recycled, possibly after minimal treatment. In fact, as subsequently discussed, a separate scenario for substantial water savings emerges, based on the combined blow-down streams.

ii) Maximization of recovery/recycling of valuable compounds

The equipment flushing streams (#51), despite their relatively small volume, appear to lend themselves for recovery of compounds/concentrates to be directly recycled to the dairy products-processing. However, appropriate processing will be required for that.

The by-product streams (comprising primarily whey proteins and lactose) were not considered for valuable compounds recovery, after specific processing, as the dairy industry (including MEVGAL) consider the sustainability of such processing questionable at present, mainly due to the relatively low price of potential products.

In view of the above considerations, the following candidate scenarios have emerged for further systematic assessment.

1. Case 1. Anaerobic/aerobic Membrane bioreactor with a capacity of 300 m^3/day (TOC_{feed}=11.060 mg/L)
2. Case 2. Anaerobic/aerobic Membrane bioreactor with a capacity of 500 m^3/day (TOC_{feed}=7.435 mg/L)
3. Case 3. Aerobic Membrane bioreactor for treatment of MEVGAL wastewater streams (Capacity=1.725 m^3/day)
4. Case 4. Submerged Ultrafiltration unit for the recovery of valuable compounds with a capacity of 40 m^3/day
5. Case 5. Reuse of cooling tower blowdown (without treatment)

4.4. Energy

Steam is produced on site with three steam boilers, 2 boilers operating at 8 bar and a smaller boiler, which is dedicated to specific processes, operating at 15 bar. Make-up water for the steam system is produced locally with RO membrane modules. As back-up, an ion exchange system is in place in case of problems with the RO unit.

At 7 different locations within the dairy plant, condensate buffer vessels are installed to collect condensate from the various steam using operations. The collected condensate is recycled to the deaerator in the boiler house. The amount of condensate retour is estimated to be around 40% (of the steam to the processes). The remaining steam/condensate is mainly lost to the WWTP and partially to the atmosphere (vents, flash steam).

The average temperature of the total effluent which is send to the aerobic WWTP on the site of MEVGAL is in the range of 20-28°C.

Scenarios for heat recovery

For the dairy plant of MEVGAL no practical opportunities for using waste or effluent streams for heat integration or a specific chemical heat pump application are identified, for the following main reasons :

- The plant is operated in batch mode (with frequent product changes) and stopped overnight, which makes it technically very complex to operate heat pumps and impractical for heat integration options.
- Except for the steam/condensate system, all water effluent streams within the dairy plant are of relatively low temperature. The use of condensate as heat source for heat integration or a CHP system will not be practical, because a condensate recycle to the boiler house is preferred with respect to energy saving.
- For reasons outlined above, the economic feasibility will be poor.

5. Methodology for assessing alternative scenarios

5.1. Assessment of the alternative scenarios

5.1.1. Approach for the scenario assessment of case 1 to 3

To verify the feasibility of the alternative scenarios, for each of the proposed scenario of case 1 to 3, a conceptual design is made and evaluated on their economics. The following general approach was used:

1. Generation of process flowsheet
2. Data gathering
3. Creating mass balance model
4. Determination of Operating Expenses (OPEX) cost and comparison with base case
5. Determination of Capital Expenditure (CAPEX)
6. Determination of the simple payback time

It is noted that a somewhat simplified approach was taken for scenario cases 4 and 5.

5.1.1.1 Generation of process flowsheet

To make a fair comparison with the base case possible, for each of the cases, a flowsheet was created with comparable battery limits and with only the relevant unit operations and streams included.

Base case flowsheet

The simplified flowsheet given in **Figure 5.1** is used to represent the base case situation. It will be used as a reference for the comparison with the assessed cases from 1 to 3. This base case flowsheet only includes the unit operations and process streams which are relevant for the comparison. Feed (fresh water intake) and (co-)product streams (by-products, effluent, and surplus sludge) are indicated in pink.

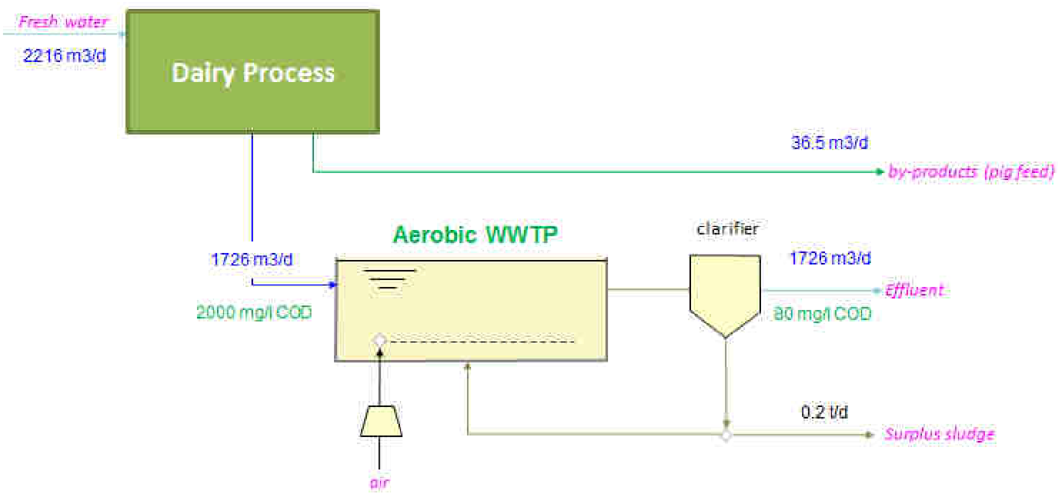

Figure 5.1. Simplified flowsheet of the current system (base case)

5.1.1.2 *Data gathering*

For making a conceptual design of a new process, specific performance data and process characteristics are needed. To facilitate the data alignment and retrieving missing process performance data, a questionnaire was prepared by PDC for CERTH and MEVGAL.

Base case process characteristics

The most important process characteristics for the base case are given in Table 5.1. The COD removal efficiency of the existing aerobic WWTP is 96%. The effluent of the WWTP, with a resulting COD value of 80 mg COD/L, is drained to a local river free of charge. Surplus sludge is disposed to an external sludge processor at a certain cost.

Table 5.1. Process characteristics Base Case

Aerobic WWTP								COD Load 3451 kg COD/d
Efficiency **aerobic** WWTP	96%	COD removal						
Specific electricity consumption	**21.3**	kWh/kg COD						
surplus sludge production	0.03	mg particulate COD/mg consumed COD						
Feed / Products	**amount**			**cost price**			**Disposal to**	
Influent aerobic WWTP	1726	m3/d	COD in	2000	mg/l			
Discharge treated effluent	1726	t/d		0	€/t		local river (COD out = 80 mg/l)	
Discharge surplus sludge	0.2	t/d		65	€/t		external sludge processor	
By-products								
Fat-free w hey	13.5	t/d		10	€/t		75% of free-fat w hey is sold as pig feed	
Whey	16	t/d		10	€/t		sold as pig feed	
UF permeate	7	t/d		10	€/t		sold as pig feed	
Utilities								
Fresh w ater (intake dairy process)	2216			0.5	€/m3			
Electricity aerobic WWTP				0.1	€/kWh			

5.1.1.3 *Mass balance model*

Based on the retrieved process characteristics and performance data, a mass balance model is generated in an Excel environment. The model is partially based on data from the existing process operations and partially on data obtained from laboratory experiments carried out by CERTH.

Base case mass balance data

The most important mass balance data for the base case are already indicated in Figure 5.1 are summarized in Table 5.2.

Table 5.2. Mass balance data - Base Case

	Flow	COD	conduc -tivity	Actual outlet		Remarks
	m3/d	mg/l	µS/cm	WWTP	Product	
truck washing	30			100%		aerobic WWTP
RO concentrate	7			100%		aerobic WWTP
blow down boiler	2			100%		aerobic WWTP
condensate loss	50			100%		aerobic WWTP
CW	50			100%		aerobic WWTP
cleaning	160			100%		aerobic WWTP
flushing	40			100%		aerobic WWTP
CIP	900			100%		aerobic WWTP
cooling water blow down	480			100%		aerobic WWTP
regeneration liquid	2			100%		aerobic WWTP
Sub-total to WWTP (m3/d)	**1721**			**1721**		
fat-free whey	18	70200	12230	25%	75%	sold as pig feed (75%)
whey	16	90000	12570	0%	100%	sold as pig feed
UF permeate	7	57600	5320	0%	100%	sold as pig feed
By-products	**36.5**	76463	11054			sold as pig feed
Total to WWTP	**1726**	2000	2500			including 25% fat-free whey
Fresh water (intake)	2216					

The total amount of wastewater sent to the aerobic WWTP is 1,726 m^3/d. This includes 25% of the fat-free whey stream which cannot be sold as pig feed (Table 5.2).

To compensate the losses at various locations (mainly evaporation losses in the cooling water system, but also some in the steam and cleaning system), the daily fresh water intake is somewhat (490 m^3/d) higher, and amounts to 2,216 m^3/d.

5.1.1.4 *Determination OPEX cost*

To determine the annual operating expenses (OPEX), all cost for raw materials, products and by-products, utilities (fuel, electricity, steam, cooling water), auxiliaries and waste disposal are calculated by multiplying the amount with the unit price and adding these up.

The selling of products (biogas) and by-products (whey, fat-free whey, UF permeate) are profits (no costs) and therefore accounted as a negative cost. The replacement of UF membranes is regarded as auxiliary cost and is also accounted for.

Base case OPEX cost

For each of the assessed cases (from 1 to 3), the OPEX is determined according to the above described procedure. The results are compared with the OPEX cost for the base case to identify where the major differences are.

The unit prices used, given in Table 5.3 in a separate column, are generally based on actual cost prices for MEVGAL. The fresh water intake for MEVGAL (with a price of 0.5 €/m3) is relatively cheap because of the fact that MEVGAL can use its own groundwater sources (6-7 wells).

The main utility consumed in the aerobic WWTP is electricity, which is predominantly (about 60-70%) used for the aeration and to a much smaller extent for pumping and driving some other equipment like scrapers. For electricity a price of 0.1 €/kWh is used.

By-products (UF permeate, whey and fat-free whey) are sold as pig feed against a price of 10 €/ton.

Besides the conventional aerobic treatment, MEVGAL also makes use of bio-augmentation (i.e. the addition of microorganisms that have the ability to biodegrade recalcitrant molecules). The monthly cost for this bio-augmentation is indicated in Table 5.3.

The surplus sludge formed during the aerobic treatment is collected and at regular intervals disposed to an external sludge processor at a cost of 65 €/t.
The effluent from the aerobic WWTP can be discharged into a local river without any cost.

Table 5.3. Estimated OPEX - Base Case

	Amount		Unit price		Cost		
	--		--		k€/yr		
Fresh water (process)	2216	m3/d	0.5	€/m3	404		
By-products discharge	36.5	t/d	10.0	€/t	-133		
Electricity aerobic WWTP	73506	kWh/d	0.1	€/kWh	2683		89%
Bioaugmentation			3500	€/month	42		
Effluent discharge	1726	m3/d	0	€/m3	0		
Surplus sludge discharge	0.2	t/d	65	€/t	5		
Total cost					3001	k€/yr	

To compare the different cases, an OPEX estimation is made only for the relevant streams.

The OPEX expenses for the base case battery limits are given in Table 5.3. The annual cost for the daily fresh water intake of 2216 m^3/d for MEVGAL's dairy process costs about 400 k€/yr. The revenues by selling 36.5 t/d of by-products (UF permeate, whey and 75% of the produced fat-free whey) amounts to about 130 k€/yr.

As can be concluded from Table 5.3, a large amount of the total operational cost for the base case is associated with the electricity consumption of the aerobic WWTP. The annual cost for the bio-augmentation is 42 k€/yr, while the disposal of the remaining surplus sludge only contributes 5 k€/yr to the total cost.

Remark:
It should be noted that in this preliminary OPEX cost estimate, the labor and maintenance cost are not taken into account.

5.1.1.5 Determination of capital cost

Cost estimate approach

There are several classes of cost estimates, ranked according to their aimed accuracy (see Table 5.4). A class 4 estimate for feasibility studies is regarded as the appropriate class for the economic evaluation of the assessed scenarios (cases 1 to 3). The methodology used by PDC for class 4 estimates is based on equipment factored models (costing curves).

Table 5.4. Classes of cost estimates, ranked according to their aimed accuracy

Estimate class	Level of project definition	End usage	Methodology	Expected accuracy range
Class 5	0% - 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	-50 to +100%
Class 4	1% - 15%	Study or feasibility	Equipment factored or parametric models	-30 to +50%
Class 3	10% - 40%	Budget, authorization or control	Semi-detailed unit cost with assembly level line items	-20 to +30%
Class 2	30% - 70%	Control or Bid/Tender	Detailed unit cost	-15 to +20%
Class 1	50% - 100%	Check Estimate or Bid/Tender	Detailed unit cost with detailed take-off	-10 to +15%

Methodology

The total equipment cost for the assessed cases 1 to 3 are estimated by performing equipment sizing on basis of the derived mass balances, followed by using PDC's in-house costing software, which is embedded in PROSYN. With this costing software, the so-called 'Bare Module Cost' (BMC) of each piece of equipment is calculated, which is principally equal to the 'Installed Equipment Cost' (IEC) used by others.

The major pieces of equipment included in the flowsheet are costed in this way. Relative small items (like e.g. pumps) are not costed separately but are accounted for with a term 'unlisted equipment' by using a certain percentage of the total equipment cost.

The equipment cost estimates are based on the following general settings:

- Cost date : Jan 2019
- Location : US Gulf coast conditions
- Currency : €
- Exchange rate : 0.88 €/US$

Based on the calculated equipment cost, the total cost of each alternative scenario is calculated by summing up all individual equipment items and adding a specific percentage for engineering cost (3%) and contingency (15%).

Remark:

It should be noted that the following potential cost factors which might contribute to the total capital investment cost (TIC) are not included in the current capital cost estimate:

- *land cost*
- *site development*
- *auxiliary buildings*
- *off-site facilities*
- *start-up expenses*
- *working capital*

6. Assessment of alternative scenarios

In the following sections, for each of the selected scenarios a general description will be given of the flowsheet with the main process characteristics as well as an economic evaluation on the basis of the estimated OPEX and equipment cost.

6.1. Case 1

6.1.1. Process flowsheet and characteristics

In Case 1 the by-products from the dairy process (fat-free whey, whey and UF permeate) with a relatively high COD content are not sold (as pig feed) but used for biogas production in an anaerobic MBR. A simplified flowsheet of the proposed process is given in Figure 6.1.

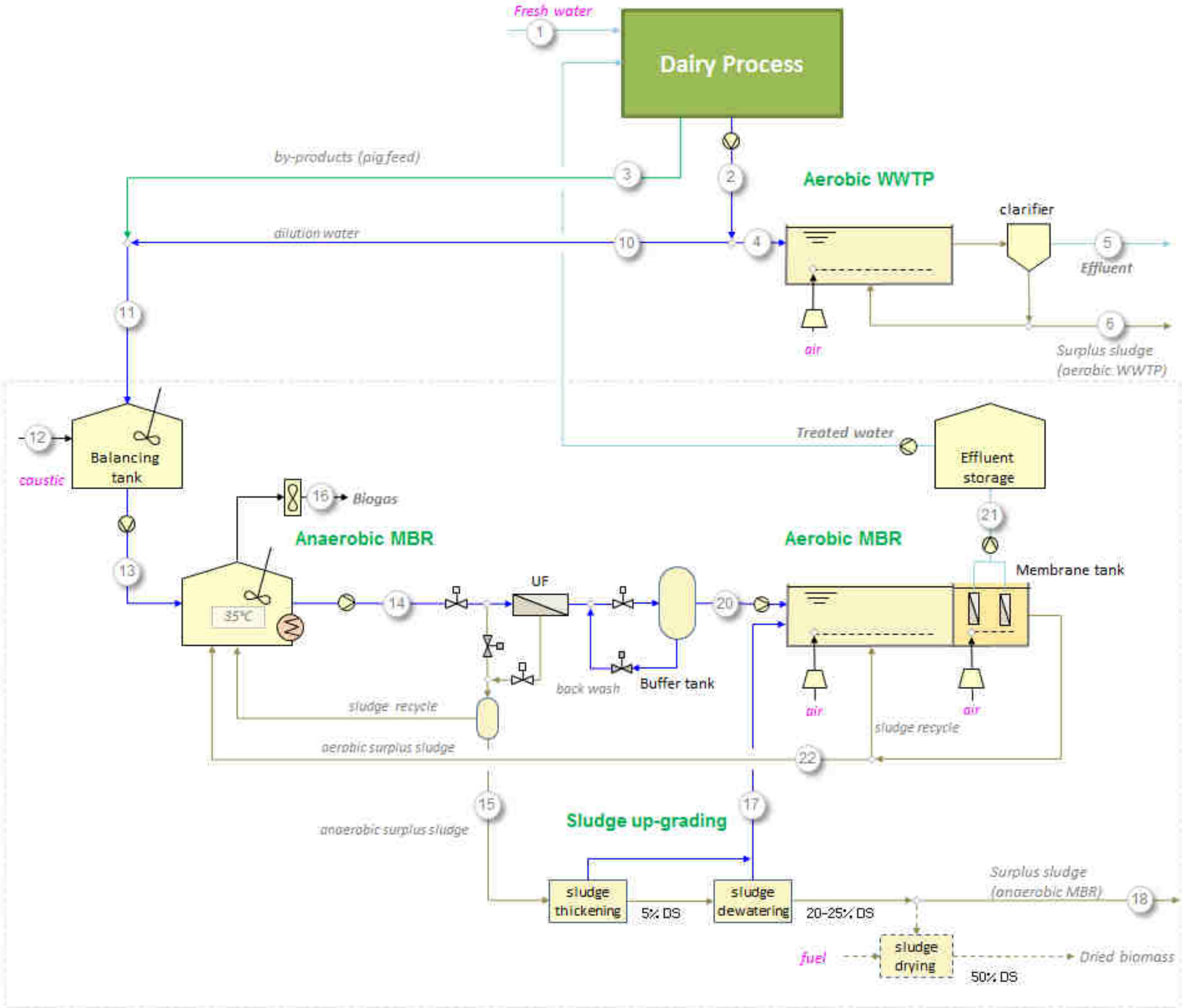

Figure 6.1. Simplified flowsheet of Case 1

The top part of Figure 6.1 already exists, the bottom part (within the dotted box) includes the added process systems for Case 1 scenario.

In total 36.5 m^3/d of by-products are available for biogas production with an average COD content of 76,460 mg COD/L. This concentration is too high as direct feed for the anaerobic MBR; therefore, this stream is first diluted, with part (263.5 m^3/d) of the wastewater (from the dairy processes) currently directed to the existing aerobic WWTP. To the mixed stream (in total 300 m^3/d after dilution) some caustic is added in the balancing tank for pH adjustment. The balancing tank is used as feed tank for the anaerobic MBR and is equipped with an agitator for mixing purposes.

In the anaerobic MBR reactor, designed for a residence time of 48 hours, a large part of the COD, from the influent wastewater and the recycled surplus sludge from the aerobic MBR, is converted into biogas. The biogas mainly consists of a mixture of methane and carbon dioxide. For calculating the energy content of the biogas, a value of 23.3 MJ/Nm^3 is taken. For transportation of the biogas, a blower is introduced. Various options are possible for using the biogas (Figure 6.2). For instance, the biogas might be used as fuel for a dryer system to convert the produced sludge into a dried biomass product, as is indicated in dotted lines in the bottom part of Figure 6.1. The biogas might also be used for utility generation, either for steam in a steam boiler or for producing electricity in a gas engine.

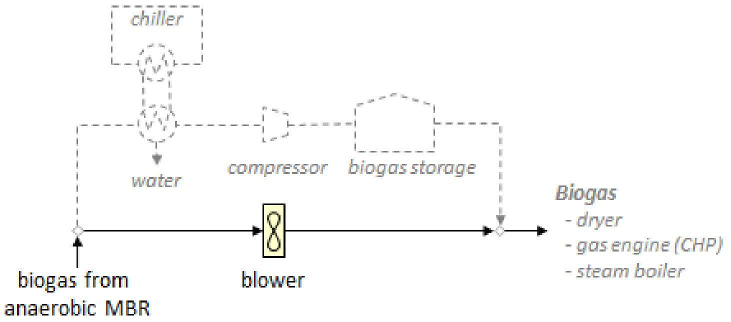

Figure 6.2. Potential biogas usage

In contrast with the biogas production, the steam demand is not continuous, but is mainly during day time. Therefore, using the biogas for electricity production in a gas engine seems a logic choice for MEVGAL. The gas engine can be regarded as a CHP unit (Combined Heat and Power) because it not only generates electricity but also produces (low temperature) heat at a level of about 80-120°C (depending on the chosen gas engine system). Within the dairy process, there are some opportunities to use this low temperature heat, e.g. for heating the CIP system and/or as utility for heating the anaerobic MBR. In both cases this will lead to a saving on steam consumption.

A potential biogas work-up, like drying the gas by cooling with a chiller unit followed by a compression step and biogas storage (for extra buffer capacity) as is indicated in Figure 6.2, is not included in the design. Also, in the current design no additional equipment concerning the biogas usage is accounted for, and the biogas is just valued in respect of its heating value.

The anaerobic MBR tank is equipped with an agitator for gentle agitation and with a heat exchanger to keep the reaction temperature at about 35°C. For calculating the utility consumption, it is assumed that average temperature of the wastewater influent is about 30°C (this might be somewhat lower in winter time, and higher in summertime). Steam (10 bar, saturated) is foreseen as utility for the heat exchanger, because no suitable waste heat stream from the process can be used for this purpose.

The effluent from the anaerobic MBR is pumped to a UF membrane system where the anaerobic sludge is separated from the water and partially recycled back to the anaerobic reactor to maintain a high sludge concentration. Based on laboratory experiments, the estimated area needed for the UF membranes is 2500 m^2. The UF membranes are automatically back-washed, at a predetermined frequency, with permeate (taken from the buffer tank directly behind the UF membrane system) to control fouling and ensure proper operation of the membrane modules. In the current design the following backwash procedure is foreseen: 4 minutes of normal operation followed by one minute of back-wash operation.

The surplus sludge from the anaerobic MBR (stream 15, Fig. 6.1) will initially have a relatively low DS content (assumed 2 wt% DS), which can be increased by using a sludge thickener followed by sludge pressing up to 20-25 wt% DS. A potential dosage of flocculants in the sludge thickener (to get stronger aggregates and better dewatering properties) is not taken into account in the current design. Furthermore, it is assumed that the sludge can be dewatered mechanically up to 25 wt% DS, and that it is then disposed to an external sludge processor (in the same way as the current sludge disposal of the aerobic WWTP).

The water coming from the sludge dewatering equipment is collected and recycled to the aerobic MBR (stream 17, Fig. 6.1). Together with the permeate from the anaerobic UF modules (stream 20, Fig. 6.1), it is fed to an aerobic MBR system consisting of an aeration basin followed by a separate membrane tank. For the aeration of the aerobic MBR, a specific electricity consumption is considered which is 60% of the electricity consumption of the existing conventional aerobic WWTP. The specific electricity consumption for the aeration in the membrane tank is much lower, because it is just used for getting a gentle agitation to prevent clogging of the submerged UF membranes. Also here, the UF membranes are used to separate sludge from the effluent. The membrane area needed is estimated to be 1560 m^2. The resulting, more concentrated, sludge is recycled back to the aerobic MBR. The surplus sludge is recycled back to the anaerobic MBR where it is partially broken down and converted to biogas.

The permeate from the submerged membrane unit in the membrane tank is temporarily stored in an effluent storage vessel and from there recycled as treated water to the dairy plant. It is assumed that the treated water can be used in the cooling water circuit, to replace part of the make-up water for the cooling towers. This will lead to a saving on the fresh water intake of the dairy processing. In the current design, it is assumed that for the recycle of treated effluent neither further purification is needed nor that additional biocides must be used in the cooling water system to suppress microbiological activity.

6.1.2. Estimation of OPEX cost for Case 1

For the conceptual design of the previously described wastewater treatment system, a mass balance model was created in Excel with the main process characteristics as presented in Table 6.1. The mass balance model is used to determine the preliminary operating expenses (OPEX), with cost (or income) for utilities, materials, auxiliaries and (co-)products.

Table 6.1. Basic process characteristics - Case 1

Aerobic WWTP (existing)							
Efficiency aerobic WWTP	96%	COD removal			Specific electricity consumption	21.3	kWh/kg COD (feed)
surplus sludge production	0.03	mg particulate COD/mg consumed COD					
Feed / Products	**amount**		**COD**				
Influent aerobic WWTP	1462	m3/d	2000				
Discharge treated effluent	1462	m3/d					
Discharge surplus sludge	0.17	t/d					
Anaerobic MBR (reactor + UF membrane)							
Efficiency anaerobic MBR	96%	COD removal			Electricity usage	slow agitation	
Residence time	48	h			Heating:	35	°C
surplus sludge production	0.02	mg particulate COD/mg consumed COD					
UF filter type	polymeric				UF filter: normal operation mode	4	min
UF filter membrane area	2500	m2			UF filter: back-wash operation mode	1	min
Feed / Products	**Flow**		**COD**		**Additives:**		
Inlet anaerobic WWTP (high COD)	36.5	m3/d	76463	mg/l	Caustic	300	kg/d
Dilution (with low COD waste water)	263.5	m3/d	2000	mg/l	Biogas production	1360	Nm3/d
Feed stream (afer mixing)	300	m3/d	11060	mg/l			
Aerobic MBR (bioreactor + UF membrane)							
Efficiency aerobic MBR	83%	COD removal			Electricity for aeration aerobic MBR	**12.8**	kWh/kg COD (feed)
					Electricity for aeration membrane tank	0.25	kWh/m3 (influent)
surplus sludge production	0.1	mg particulate COD/mg consumed COD					
UF filter type	polymeric				UF filter (submerged)	with back-wash	
UF filter membrane area	1560	m2			Work-up anaerobic + aerobic sludge:	as indicated in figure	
Feed / Products	**Flow**		**COD**				
Inlet aerobic bioreactor	300	m3/d	442.4	mg/l			

An overview of the estimated operational costs are presented in Table 6.2. The unit prices used are given in a separate column, and are generally based on the actual cost prices for MEVGAL. The fresh water intake for MEVGAL (with a cost price of 0.5 €/m3) is relatively cheap. For electricity a price of 0.1 €/kWh is used and for steam 15 €/t.

With respect to the (co-)products, the biogas produced is valued against its heating value by using a caloric value of 23.3 MJ/Nm3 and a price of 10 €/GJ. For the disposal of surplus sludge a price of 65 €/t is used for sludge coming from the existing WWTP as well as for the sludge from the anaerobic MBR.

With respect to the cost of materials, a cost price for caustic of 50 €/ton is used (20 wt% solution). For both the UF modules in the anaerobic as well as in the aerobic MBR, polymeric membranes are used. To guarantee a proper operation, it is assumed that the polymeric membranes are replaced once per 5 years. For this replacement a cost price of 100 €/m^2 is taken into account.

To compare the differences of Case 1 with the base case, Table 6.2 includes the calculated values for the base case as well. The estimated overall OPEX cost for case 1 is 2748 k€/yr.

When comparing this with the OPEX cost for the base case (3001 k€/yr), a saving of about 250 k€/yr results. A part of this saving can be attributed to the saving of 300 m^3/d of fresh water, equivalent with an annual saving of 54 k€/yr.

Table 6.2. Estimation OPEX cost for Case 1

Estimation OPEX cost	Amount	Unit price	Case 1	Base case
	--	--	k€/yr	k€/yr
Process				
Fresh water (process)	1916 m3/d	0.5 €/m3	350	404
By-products discharge	0 t/d	10.0 €/t	0	-133
Aerobic WWTP (existing)				
Electricity aerobic WWTP	62281.2 kWh/d	0.1 €/kWh	2273	2683
Bioaugmentation		3500 €/month	36	42
Effluent discharge	1462 m3/d	0 €/m3	0	0
Surplus sludge discharge	0.2 t/d	65 €/t	4	5
Anaerobic + aerobic MBR				
Electricity aerobic MBR blower	1695 kWh/d	0.1 €/kWh	62	
Electricity membrane tank blower	75 kWh/d	0.1 €/kWh	3	
Total elec. pumps & biogas blower	573 kWh/d	0.1 €/kWh	21	
Total electricity agitation	168 kWh/d	0.1 €/kWh	6	
Steam for preheating anaerobic MBR	3.1 t/d	15 €/t	17	
Replacement polymeric membranes	812 m2/jr	100 €/m2	81	
Caustic (20 wt% concentration)	300 kg/d	0.05 €/kg	5	
Anaerobic surplus sludge discharge	0.3 t/d	65 €/t	6	
Biogas production	1365 Nm3/d	23.3 MJ/Nm3		
	32 GJ/d	10 €/GJ	-116	
Total cost			**2748 k€/yr**	**3001**
Savings compared to base case			253 k€/yr	

A significant difference is obtained from the by-products. In the base case, by-products are sold as pig feed resulting in an annual income of 133 k€/yr. In case 1, however, these by-products are not sold anymore but converted into biogas. This results in a revenue of 116 k€/yr, which is (by 17 k€/yr) less than for the case of selling pig feed.

By introducing the anaerobic and aerobic MBR, 264 m^3/d of wastewater is needed to dilute the by-products and arrive at the desired COD concentration. Due to this dilution water, the amount of wastewater to be treated in the existing aerobic WWTP is reduced proportionally (1462 m^3/d instead of 1726 m^3/d, a reduction of 15%). Assuming that the electricity consumption of the aerobic WWTP is proportional with the influent flow, the electricity consumption will be reduced from 2683 k€/yr (base case) to 2273 k€/yr, resulting in an annual saving of 410 k€/yr. Due to the reduced capacity of the WWTP, the costs for the bio-augmentation and surplus sludge disposal will be also reduced by 15%.

Additional cost for operating the anaerobic and aerobic MBR are for electricity (in total 92 k€/yr for aeration blowers, 5 main pumps, biogas blower, and agitation), steam (17 k€/yr for heating up 300 m^3/d from 30 to 35°C), materials (11 k€/yr for caustic and surplus sludge disposal) and the annual replacement of the polymeric UF membranes (81 k€/yr for replacing 2500 m^2 in the anaerobic and 1560 m^2 in the aerobic MBR).

6.1.3. Total equipment cost - Case 1

The capital cost estimation starts with equipment selection and a proper sizing of the equipment on the basis of the generated mass balance. The cost estimate includes the major pieces of equipment. Smaller items like pumps and valves are not costed separately, but are taken care of by using a certain factor for unlisted equipment. In this case 5% is used as factor for the unlisted equipment (Table 6.3).

For sizing the aerobic MBR the same residence time (48 h) is used as for the anaerobic MBR. As material for the anaerobic MBR carbon steel was selected, while for the aerobic MBR it is assumed that concrete will be a good choice (as is used in the existing WWTP). For all other equipment also carbon steel was selected as material, e.g. for membrane modules which are polymeric.

As mentioned before, certain pieces of equipment are not included in this cost estimate:

- Equipment for work-up of biogas (drying, chiller, compressor, biogas storage)
- Equipment for the usage of biogas (e.g. gas engine)
- Equipment for drying surplus sludge to a higher DS content

Table 6.3. Estimated equipment cost - Case 1

Equip ID	Description	Number of units	Design	material	Cost k€	
V-1	Balancing tank	1	V = 31 m3; 0 h residence time	Carbon Steel	17	1%
M-1	Agitator balancing tank	1	Stuffing box agitator	carbon steel	45	1%
R-1	Anaerobic MBR	1	V = 923 m3; 48 h residence time	Carbon Steel	262	9%
M-2	Agitator anaerobic MBR	1	Stuffing box agitator	carbon steel	30	1%
HE-1	preheat anaerobic MBR	1	Area = 1 m2	cs/cs	7	0%
C-1	Biogas fan	1	centrifugal radial	carbon steel	8	0%
UF-1	UF membranes (anaerobic MBR	1	Filter area = 2500m2;		1123	37%
V-2	Buffer tank	1	L = 4.6 m; D = 1.5 m	carbon steel	95	3%
R-2	Aerobic MBR	1	V = 666 m3; 48 h residence time	Concrete	126	4%
C-2	Air compressor aerobic MBR	1	centrifugal (turbo)	carbon steel	203	7%
V-3	Membrane tank	1	V = 25 m3; 0.1 h residence time	Carbon Steel	15	0%
C-3	Air compressr membrane tank	1	centrifugal (turbo)	carbon steel	31	1%
UF-2	UF membranes (aerobic MBR)	1	Filter area = 1560m2;		732	24%
V-4	Effluent storage tank	1	V = 799 m3; 2 h residence time	Carbon Steel	96	3%
V-5	sludge recycle buffer vessel	1	L = 1.9 m; D = 0.6 m	carbon steel	27	1%
V-6	sludge thickening	1	L = 3.4 m; D = 1.1 m	carbon steel	62	2%
P-1	Surplus sludge press	1	Roll press	carbon steel	29	1%
	Sub-total equipment cost				**2908**	
			Unlisted equipment :	5%	145	5%
	Total equipment cost				**3,054**	100%

From Table 6.3, it can be concluded that the total equipment cost exceeds 3 M€. The costs are dominated by the cost for the UF membrane modules, with 37% of the total equipment cost for the anaerobic membranes (equivalent with 1123 k€) and 24% for the aerobic membranes (732 k€).

The anaerobic and aerobic reactor with the air compressor are the next expensive items, representing together about 20% of the total equipment cost.

6.1.4. Payback time Case 1

From the estimated, in preceding sections, OPEX cost (actually the calculated savings compared to the base case) and total equipment cost, the payback time for this alternative scenario can be calculated.

To obtain the total capital cost for the proposed modification, first the engineering cost (taken as 3% of the total equipment cost) and contingency cost (15% of the total equipment cost) are added, resulting in a total capital cost of 3.6 M€.

Table 6.4 Payback time - Case 2

Savings	Amount	Amount	Price	Saving		
Total savings (compared to base case)				253	k€/yr	
Modifications						
Total equipment cost				3,054		*)
Engineering			*3%*	92	k€	
Contingency			*15%*	458	k€	
Total cost modifications *)				**3,604**	k€	
Payback time				**14.2**	**yr**	

**) Excluding equipment for utilization of biogas and equipment for sludge drying*

With the calculated savings of about 250 k€, the resulting payback time is 14 years.

6.2. Case 2

6.2.1. Process flowsheet and characteristics - Case 2

In case 2 the anaerobic part of the treatment system is kept the same as for case 1, which means that a mixture of 300 m3/d of by-products and dilution water with an average COD content of 11,060 mg COD/L has to be treated. The main difference is that the remaining of the wastewater effluent (i.e. minus the subtracted dilution water) is not fed to the existing aerobic WWTP, but to the new aerobic MBR unit after mixing with the anaerobic MBR effluent as is indicated in Figure 6.3. The existing WWTP is thus not used anymore, while the capacity of the aerobic MBR is significantly increased from 300 to 1,762 m^3/d and the COD load even more (increase from 133 to 3056 kg COD/d).

The COD load of the aerobic MBR is for this case more or less comparable with the COD load of the anaerobic MBR (3316 kg COD/d).

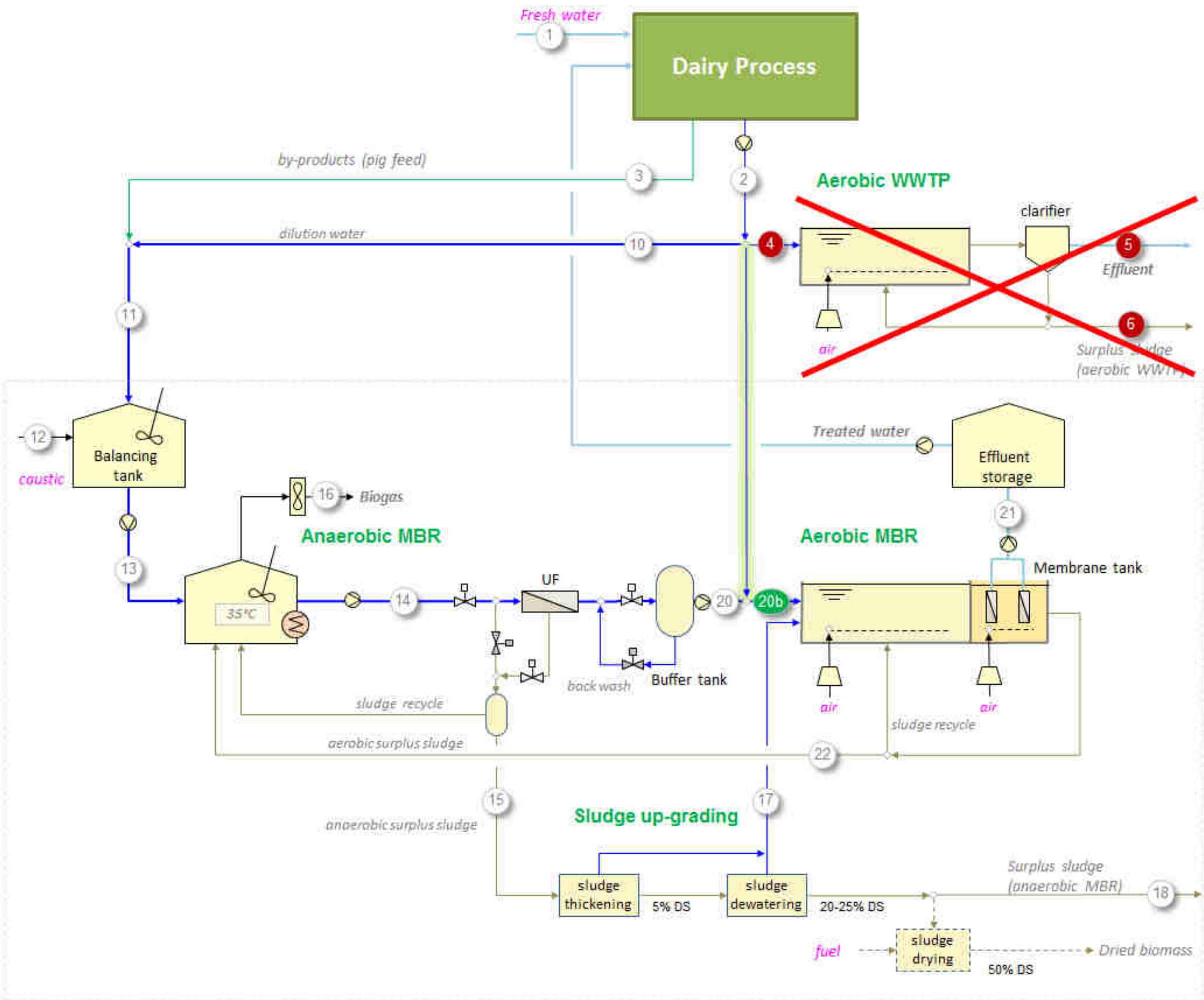

Figure 6.3. Simplified flowsheet of case 2

Except for the change in flow distribution, the rest of the process characteristics are kept the same as for case 1 (see Table 6.1).

6.2.2. OPEX cost - Case 2

An updated OPEX estimation was generated according to the implemented changes. The total OPEX cost calculated for this case 2 appears to be 1824 k€/yr (Table 6.5).

Table 6.5. OPEX estimation - Case 2

	Amount	Unit price	Cost	Base case
	--	--	k€/yr	k€/yr
Process				
Fresh water (process)	454 m3/d	0.5 €/m3	83	404
By-products discharge	0 t/d	10.0 €/t	0	-133
Aerobic WWTP (existing)				
Electricity aerobic WWTP	0 kWh/d	0.1 €/kWh	0	2683
Bioaugmentation		0 €/month	0	42
Effluent discharge	m3/d	0 €/m3	0	0
Surplus sludge discharge	0.0 t/d	65 €/t	0	5
Anaerobic + aerobic MBR				
Electricity aerobic MBR blower	39113 kWh/d	0.1 €/kWh	1428	
Electricity membrane tank blower	440 kWh/d	0.1 €/kWh	16	
Total elec. pumps & biogas blower	1269 kWh/d	0.1 €/kWh	46	
Total electricity agitation	168 kWh/d	0.1 €/kWh	6	
Steam for preheating anaerobic MBR	3.1 t/d	15 €/t	17	
Replacement polymeric membranes	3829 m2/jr	100 €/m2	383	
Caustic (20 wt% concentration)	300 kg/d	0.05 €/kg	5	
Anaerobic surplus sludge discharge	0.3 t/d	65 €/t	6	
Biogas production	1484 Nm3/d	23.3 MJ/Nm3		
	35 GJ/d	10 €/GJ	-126	
Total cost			**1864 k€/yr**	**3001**
Savings compared to base case			1136 k€/yr	

When comparing this with the base case (3001 k€/yr), a saving of 1177 k€/yr results. A part of this saving can be attributed to the saving of 1762 m^3/d of fresh water, equivalent with an annual saving of 322 k€/yr, because for this case it was initially assumed that all of the treated water could be recycled to the dairy process. This is a matter to be reconsidered after the pilot tests at MEVGAL site.

Because the existing aerobic WWTP is not used anymore in this conceptual design, a relatively large saving can be achieved on the electricity cost (2683 k/yr) and also some on the bio-augmentation (42 k€/yr) and the surplus sludge discharge cost (5 k€/yr).

On the other hand, the electricity consumption for the aerobic MBR increases substantially (1428 k€/yr), also when compared with case 1 (see Table 6.2), because of the increased load. Also as a consequence of this, the replacement cost for the polymeric UF membranes increases substantially from 81 k€/yr (Case 1, Table 6.2) to 383 k€/yr for this case.

Remark:
In this conceptual design the resulting COD content of the aerobic MBR effluent is calculated to be 87mg COD/L, which might be too high for direct reuse in most of the water demanding operations in the dairy processes (especially for make-up steam system, cleaning, flushing and CIP system). Also reuse for the cooling towers (which has in principle the lowest quality demand in the dairy operations) may be a logical option, but even this could be problematic. The quality of aerobic MBR effluent will be reconsidered after the pilot tests at MEVGAL site.

6.2.3. Equipment cost and payback time - Case 2

The estimated equipment cost for Case 2, presented in Table 6.6, amounts to about 12.5 M€, including an allowance of 5% for unlisted equipment (among other for pumps). Also here, as in Case 1, additional equipment cost (e.g. gas engine) for making use of the produced biogas is not taken into account.

Table 6.6. Estimated equipment cost - Case 2

Equip ID	Description	Number of units	Design	material		Cost k€	
V-1	Balancing tank	1	V = 31 m3; 2 h residence time	Carbon Steel		17	0%
M-1	Agitator balancing tank	1	Stuffing box agitator	carbon steel		45	0%
R-1	Anaerobic MBR	1	V = 923 m3; 48 h residence time	Carbon Steel		262	2%
M-2	Agitator anaerobic MBR	1	Stuffing box agitator	carbon steel		30	0%
HE-1	preheat anaerobic MBR	1	Area = 1 m2	cs/cs		7	0%
C-1	Biogas fan	1	centrifugal radial	carbon steel		8	0%
UF-1	UF membranes (anaerobic MBR)	1	Filter area = 2525 m2;			1134	8%
V-2	Buffer tank	1	L = 4.6 m; D = 1.5 m	carbon steel		95	1%
R-2	Aerobic MBR	1	V = 3922 m3; 48 h residence time	Concrete		430	3%
C-2	Air compressor aerobic MBR	1	axial	carbon steel		5238	35%
V-3	Membrane tank	1	V = 147 m3; 2 h residence time	Carbon Steel		36	0%
C-3	Air compressor membrane tank	1	centrifugal (turbo)	carbon steel		68	0%
UF-2	UF membranes (aerobic MBR)	1	Filter area = 16616 m2;			6284	42%
V-4	Effluent storage tank	1	V = 4699 m3; 48 h residence time	Carbon Steel		320	2%
V-5	Sludge recycle buffer vessel	1	L = 1.9 m; D = 0.6 m	carbon steel		27	0%
V-6	Sludge thickening	1	L = 3.4 m; D = 1.1 m	carbon steel		62	0%
P-1	Surplus sludge press	1	Roll press	carbon steel		29	0%
	Sub-total equipment cost					**14092**	
				Unlisted equipment:	5%	705	5%
	Total equipment cost					**14,797**	100%

Also here the cost for the UF membrane modules are the main contributors to the total equipment cost, especially the membranes for the aerobic MBR. The sizing of the membrane area (16,616 m^2) is done proportionally with the surplus sludge production, with case 1 as reference. The costs of these aerobic UF membrane modules already accounts for 42% of the total equipment cost, while the membranes in the anaerobic MBR accounts for 8%.

In addition to the UF membranes, the new air compressor for the aerobic MBR appears to be relatively expensive, contributing by 35% to the total equipment cost. The calculated capacity of the compressor is 1,630 kW. Here a centrifugal compressor type was selected (an axial compressor would be 40% more expensive).

The anaerobic and aerobic reactors and the effluent storage tank are the next costly items, together costing about 1 M€.

On the basis of the savings compared to the base case and the estimated total equipment cost, the computed payback time for this scenario is 15.4 years (Table 6.7), which is a bit more than the payback time of Case 1 (14.2 years, table 6.4).

Table 6.7. Payback time - Case 2A

Savings	Amount	Amount	Price	Saving	
Total savings (compared to base case)				1136 k€/yr	**)
Modifications					
Total equipment cost				14,797	*), ***)
Engineering			3%	444 k€	
Contingency			15%	2220 k€	
Total cost modifications *)				**17,460** k€	
Payback time				**15.4 yr**	

*) Excluding equipment for utilization of biogas and equipment for sludge drying
**) Including savings on recycle treated water
***) Inluding new compressor for aeration aerobic MBR

6.2.4. Case 2B

Because the existing aerobic WWTP is not used anymore in this conceptual design, it might be an option to *use the air compressor from the existing WWTP* for the aeration of the new aerobic MBR. This will save 3.7 M€ on compressor cost, arriving at a total equipment cost of 8.5 M€ (Table 6.8). The equipment cost are for this case even more dominated by the UF membrane cost (78% of the total cost).

Table 6.8: Equipment cost for alternative case 2A (with re-use of existing air compressor)

Equip ID	Description	Number of units	Design	material	Cost k€	
V-1	Balancing tank	1	V = 31 m3; 2 h residence time	Carbon Steel	17	0%
M-1	Agitator balancing tank	1	Stuffing box agitator	carbon steel	45	0%
R-1	Anaerobic MBR	1	V = 923 m3; 48 h residence time	Carbon Steel	262	3%
M-2	Agitator anaerobic MBR	1	Stuffing box agitator	carbon steel	30	0%
HE-1	preheat anaerobic MBR	1	Area = 1 m2	cs/cs	7	0%
C-1	Biogas fan	1	centrifugal radial	carbon steel	8	0%
UF-1	UF membranes (anaerobic MBR)	1	Filter area = 2525 m2;		1134	12%
V-2	Buffer tank	1	L = 4.6 m; D = 1.5 m	carbon steel	95	1%
R-2	Aerobic MBR	1	V = 3922 m3; 48 h residence time	Concrete	430	5%
~~C-2~~	~~Air compressor aerobic MBR~~	~~1~~	~~axial~~	~~carbon steel~~		0%
V-3	Membrane tank	1	V = 147 m3; 2 h residence time	Carbon Steel	36	0%
C-3	Air compressor membrane tank	1	centrifugal (turbo)	carbon steel	68	1%
UF-2	UF membranes (aerobic MBR)	1	Filter area = 16616 m2;		6284	68%
V-4	Effluent storage tank	1	V = 4699 m3; 48 h residence time	Carbon Steel	320	3%
V-5	Sludge recycle buffer vessel	1	L = 1.9 m; D = 0.6 m	carbon steel	27	0%
V-6	Sludge thickening	1	L = 3.4 m; D = 1.1 m	carbon steel	62	1%
P-1	Surplus sludge press	1	Roll press	carbon steel	29	0%
	Sub-total equipment cost				**8854**	
			Unlisted equipment:	5%	443	5%
	Total equipment cost				**9,297**	100%

As a result of this alternative scenario, the payback time is reduced by almost 6 4 years from almost 15.4 to 9.7 years (Table 6.9).

Table 6.9. Payback time Case 2B

Savings	**Amount**	**Amount**	**Price**	**Saving**	
Total savings (compared to base case)				1136 k€/yr	**)
Modifications					
Equipment cost				9,297 k€	*), ***)
Engineering			*3%*	279 k€	
Contingency			*15%*	1395 k€	
Total cost modifications *)				**10,970** k€	
Payback time				**9.7 yr**	

**) Excluding equipment for utilization of biogas and equipment for sludge drying*
***) Including savings on recycle treated water*
****) Excluding new compressor for aeration aerobic MBR*

6.2.5. Case 2C

As mentioned in Subsection 6.2.2 under the remark, the quality of the treated water might is too low to be re-used in the dairy process. If this is indeed the case, it looks like the treated water should be disposed to the local river, in the same way as it is done currently. For this situation, which seems a realistic scenario, the total savings compared to the base case will decrease accordingly (i.e. 322 k€/yr less saving), resulting in a payback time of 13.5 years, as can be concluded from Table 6.10. This is only a little bit better than the previously described Case 2A (Table 6.7).

Table 6.10. Payback time Case 2C

Savings	Amount	Amount	Price	Saving	
Total savings (compared to base case)				815 k€/yr	**)
Modifications					
Total equipment cost				9,297	*), ***)
Engineering			*3%*	279 k€	
Contingency			*15%*	1395 k€	
Total cost modifications *)				**10,970** k€	
Payback time				**13.5 yr**	

*) Excluding equipment for utilization of biogas and equipment for sludge drying
**) Excluding savings on recycle treated water
***) Excluding new compressor for aeration aerobic MBR

6.3. Case 3

The reasoning underpinning of this scenario is the same as for case 1 (for flowsheet see Figure 6.1). The main difference is that in this case the amount of dilution water is increased by 200 m3/d from 264 to 464 m^3/d, so that the total feed mixture to the balancing tank is 500 m^3/d.

By taking some extra water from the aerobic WWTP for the dilution, the COD load is shifted a bit more from the aerobic WWTP to the anaerobic and aerobic MBR system. Because of the extra dilution, the COD concentration of the influent to the anaerobic MBR decreases (from 11,060 mg COD/L in case 1 to 7,436 mg COD/L). Assuming an identical efficiency of the anaerobic MBR as for case 1, the COD of the effluent from the anaerobic MBR is reduced proportionally after two days residence time (COD reduction from 442 to 297 mg COD/L). After treatment in the anaerobic and aerobic MBR, it is assumed that the treated water (500 m^3/d) is recycled back to the dairy plant for re-use as cooling water make-up.

6.3.1. OPEX cost - Case 3

An estimation of the resulting OPEX for Case 3 is given in Table 6.11. The total OPEX cost calculated for this case is 2425 k€/yr.

Table 6.11. OPEX estimation - Case 3

Estimation OPEX cost	Amount --	Unit price --	Case 3 k€/yr	Base case k€/yr	case-3 saving k€/yr	case-1 saving k€/yr
Process						
Fresh water (process)	1716 m3/d	0.5 €/m3	313	404	91	55
By-products discharge	0 t/d	10.0 €/t	0	-133	-133	-133
Aerobic WWTP (existing)						
Electricity aerobic WWTP	53761 kWh/d	0.1 €/kWh	1962	2683	721	410
Bioaugmentation		3500 €/month	31	42	11	6
Effluent discharge	1262 m3/d	0 €/m3	0	0	0	0
Surplus sludge discharge	0.1 t/d	65 €/t	3	5	1	1
Anaerobic + aerobic MBR						
Electricity aerobic MBR blower	1900 kWh/d	0.1 €/kWh	69		-69	-62
Electricity membrane tank blower	125 kWh/d	0.1 €/kWh	5		-5	-3
Total elec. pumps & biogas blower	795 kWh/d	0.1 €/kWh	29		-29	-21
Total electricity agitation	280 kWh/d	0.1 €/kWh	10		-10	-6
Steam for preheating anaerobic MBR	5.2 t/d	15 €/t	29		-29	-17
Replacement polymeric membranes	911 m2/jr	100 €/m2	91		-91	-81
Caustic (20 wt% concentration)	300 kg/d	0.05 €/kg	5			
Anaerobic surplus sludge discharge	0.3 t/d	65 €/t	7		-12	-12
Biogas production	1529 Nm3/d	23.3 MJ/Nm3				
	36 GJ/d	10 €/GJ	-130		130	116
Total cost			**2425 k€/yr**	**3001**		
Savings compared to base case			576 k€/yr		576	253

When compared to the base case, the expected savings for this case are approx. 576 k€/yr. For case 1 the savings compared to the base case amounted to 253 k€; thus, it can be concluded that the effect of the extra dilution is an increase of the savings by more than a factor 2.

The two columns at the right-hand side of Table 6.11, show the differences in savings for case 1 and case 3. The majority of savings result from savings in the fresh water consumption (36 k€/yr extra saving), savings in the electricity for the aerobic WWTP (311 k€/yr extra savings) and increased biogas production (14 k€/yr extra savings), while the operation cost for the anaerobic and aerobic MBR increases somewhat due to the slightly increased utility consumption (electricity and steam) and the membrane replacement cost.

6.3.2. Equipment cost and payback time - Case 3

For case 3 the estimated equipment cost, presented in Table 6.12, amounts to about 3317 k€, including 5% for unlisted equipment. Comparing this with the estimated cost for case 1 (3054 k€, see Table 6.3), the total equipment cost is 8.6% higher for case 3.

Table 6.12. Estimated equipment cost - Case 3

Equip ID	Description	Number of units	Design	material	Cost k€	
V-1	Balancing tank	1	V = 52 m3; 0 h residence time	Carbon Steel	21	1%
M-1	Agitator balancing tank	1	Stuffing box agitator	carbon steel	45	1%
R-1	Anaerobic MBR	1	V = 1538 m3; 48 h residence time	Carbon Steel	365	11%
M-2	Agitator anaerobic MBR	1	Stuffing box agitator	carbon steel	30	1%
HE-1	preheat anaerobic MBR	1	Area = 1.3 m2	cs/cs	7	0%
C-1	Biogas fan	1	centrifugal radial	carbon steel	8	0%
UF-1	UF membranes (anaerobic MBR)	1	Filter area = 2500m2;		1123	34%
V-2	Buffer tank	1	L = 5.4 m; D = 1.8 m	carbon steel	125	4%
R-2	Aerobic MBR	1	V = 1109 m3; 48 h residence time	Concrete	165	5%
C-2	Air compressor aerobic MBR	1	centrifugal (turbo)	carbon steel	226	7%
V-3	Membrane tank	1	V = 42 m3; 0.1 h residence time	Carbon Steel	19	1%
C-3	Air compressr membrane tank	1	centrifugal (turbo)	carbon steel	36	1%
UF-2	UF membranes (aerobic MBR)	1	Filter area = 1560m2;		732	22%
V-4	Effluent storage tank	1	V = 1333 m3; 2 h residence time	Carbon Steel	133	4%
V-5	sludge recycle buffer vessel	1	L = 2 m; D = 0.7 m	carbon steel	29	1%
V-6	sludge thickening	1	L = 3.6 m; D = 1.2 m	carbon steel	65	2%
P-1	Surplus sludge press	1	Roll press	carbon steel	29	1%
	Sub-total equipment cost				**3159**	
			Unlisted equipment:	5%	158	5%
	Total equipment cost			**Total equipment cost:**	**3,317**	100%

As might be expected, the cost for the UF membrane modules are again the most expensive items, followed by the anaerobic reactor and aerobic reactor and air compressor.

On the basis of the savings compared to the base case and the estimated total equipment cost, the estimated payback time for this scenario is 6.8 years (Table 6.13), which is half of the payback time of case 1 (14.2 years, table 6.4).

Table 6.13. Payback time - Case 3

Savings	Amount	Amount	Price	Saving	
Total savings (compared to base case)				576 k€/yr	
Modifications					
Total equipment cost				3,317	
Engineering			3%	100 k€	
Contingency			15%	498 k€	*)
Total cost modifications *)				**3,914** k€	
Payback time				**6.8 yr**	

**) Excluding equipment for utilization of biogas and equipment for sludge drying*

This reduced payback time is of course due to the more than doubled total savings (compared to the base case), while the equipment cost increase is only marginal.

Conclusion of Cases 1-3

From the investigated cases, it can be concluded that case 3 is the most promising. The recycled water to the cooling water circuit (500 m^3/d, 51 mg COD/L) is about half of the total make-up water needed (960 m^3/d); thus, the recycle is diluted with about the same amount (460 m^3/d) of fresh make-up water with 26 mg COD/L as resulting concentration.

6.4. Case 4 – Recovery of valuable compounds

6.4.1. Process flow diagram

To maximise the recovery of valuable compounds, collected effluents of equipment flushing process (presently directed to WWTP) are sent to a stainless steel tank (T-01, Figure 6.4) that meets hygiene standards. These effluents (essentially diluted milk and yogurt) are concentrated in a submerged ultrafiltration. This concentrate can be recycled to the dairy products processing, thus reducing the loss of valuable compounds of the dairy plant. Figure 6.4, provides a flow diagram of the proposed process unit.

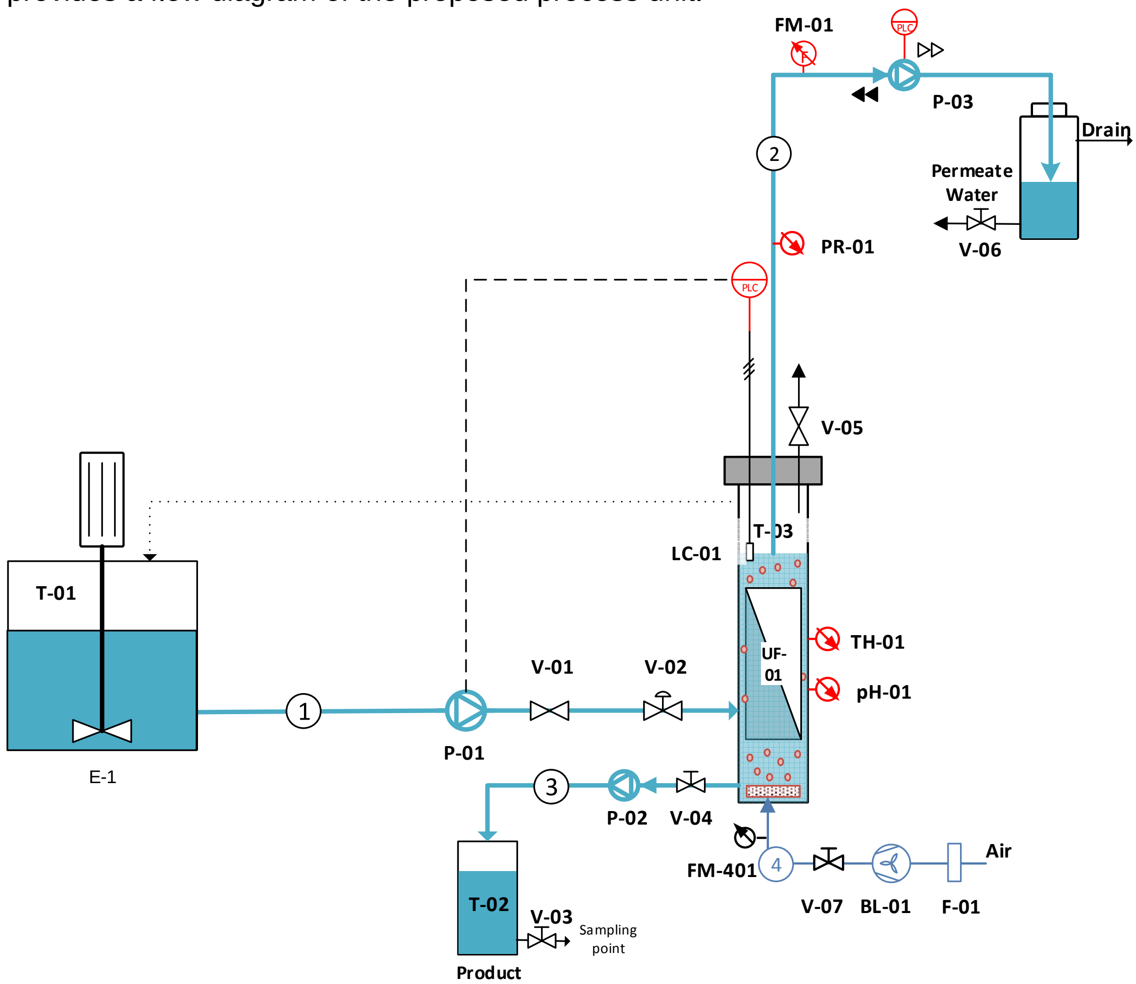

Figure 6.4. Process flow diagram of the submerged UF membrane unit

A total amount of 40 m^3/day flushing stream is available for the recovery of valuable compounds to be recycled. Based on the results of laboratory tests, a concentration factor of 8-10 is necessary in order to bring the feed to a concentration similar to that of main process products. Therefore, approx. 6 m^3/day of concentrate will be produced for recycling.

The feed stream is collected in an agitated tank and with a centrifugal pump it is transferred into the membrane tank. A positive displacement pump facilitates permeation through the pores of the membrane into a permeate tank. The membrane surface (based on the laboratory tests) needed is 280 m^2. A certain quantity of the permeate, collected in the permeate tank, is used for backwashing the membrane module. Backwashing protocol involves periodic 1 min reversed/backwashing flow after 4min of normal filtration. When the suitable concentration factor of feed stream is achieved, the concentrated product is transferred to the dairy processing. The permeate stream from the submerged unit is collected in the permeate tank and transferred to the WWTP for further treatment.

6.4.2. OPEX cost - Case 4

For the design of the submerged UF unit, mass balances were used to determine the preliminary operational cost (OPEX) of the unit. An overview of the operational parameters is included in Table 6.14.

Table 6.14. Key process characteristics for Case 4

Submerged Ultrafiltration unit				
Efficiency submerged unit	90%	COD removal		
Hydraulic Retention Time (HRT)	25	min		
Electricity for aeration	12.8	KWh/Kg COD (feed)		
UF filter type	polymeric			
UF filter area	280	m^2		
Operation/Backwash interval time	4:1	min/min		
Concentration factor	10			
Feed / Products	**Flow**		**COD**	
Inlet submerged UF	40	m^3/day	20,000	mg/L
Concentrate stream	4	m^3/day	180,000	mg/L
Permeate stream	36	m^3/day	2,000	mg/L

The estimated operational cost for the submerged Ultrafiltration unit is presented in Table 6.15, where the most important categories of expenses are included [5,6]. It is also assumed that the concentrated stream has similar quality characteristic with milk and therefore the commercial price of milk is used (0.6 €/L) to determine the revenue.

Table 6.15. Estimated OPEX for Case 4

Estimation OPEX cost	**Amount**		**Unit price**		**Cost k€/yr**
Electricity submerged UF blower	226	KWh/day	0.1	€/KWh	-8
Electricity for pumps	76.4	KWh/day	0.1	€/KWh	-3
Total Electricity for agitation	22.4	KWh/day	0.1	€/KWh	-1
Electricity for cooling purposes	93	KWh/day	0.1	€/KWh	-3
Membrane replacement	56	m^2/yr	80	€/m2	-4
Product	2	m^3/day	600	€/m^3	438
Total					418

6.4.3. Total CAPEX - Case 4

The estimated total capital cost includes the major pieces of equipment as listed in Table 6.16. Items of smaller value such as screens and valves are not listed separately, but they are accounted for by including them in the “others” category. This type of expenses represents 5% of the total unit cost.

Table 6.16. Estimated CAPEX for Case 4

	Description	Design		Material	Cost (K€)	% Cost
	Balancing tank	3	m^3	Stainless steel	15	19%
	Agitator balancing tank	stuffing box agitator		Stainless steel	3	4%
	Submerged MBR tank	1	m^3	Stainless steel	5	6%
	UF membranes	280	m^2	Polymeric	22	28%
	Permeate tank	300	L	Stainless steel	2	2%
	Concentrate tank	300	L	Stainless steel	2	2%
	Pumps				2	2%
	Blower				4	4%
	Diffusers				5	7%
	Sensors				16	20%
	Others				4	5%
Total cost	**Total cost**				**80**	**100%**

Concluding remarks

It is readily concluded that substantial benefits would result from the implementation of a submerged ultrafiltration membrane technology in the dairy industry. The estimated capital cost is relatively low (in the order of 100K€), as well as the operational cost (roughly 20k€/year). On the other hand, the revenue from the concentrated product is relatively high (~400k€/year). However, this value is likely to be reduced in practice due to the difficulty in collecting all the available flushing streams of the dairy plant. In addition, the existence of a variety of dairy products (and flushing streams) may create extra difficulties in the efficient operation of the ultrafiltration unit. Therefore, it is important to conduct tests with a pilot unit under realistic conditions in order to identify possible operating problems that may arise during the operation, such as membrane fouling tendency and required chemical cleaning frequency; the latter can significantly deteriorate the efficiency of the membrane system and consequently the cost-effectiveness of the process.

6.5. Case 5

Cooling water blowdown

Cooling tower bleed-off/blowdown is the removal of a portion of the water in the basin of the cooling tower system; this stream is usually directed to the drain, while simultaneously replacing it with fresh make-up water, as shown in Figure 6.5. This make-up water is usually pre-treated to remove hardness salts; in the MEVGAL plant, this water is treated in an ion-exchange facility. In this manner, the concentration of scale forming salts in the basin is controlled to avoid detrimental scale formation on the heat exchange tubes, where some evaporation also takes place

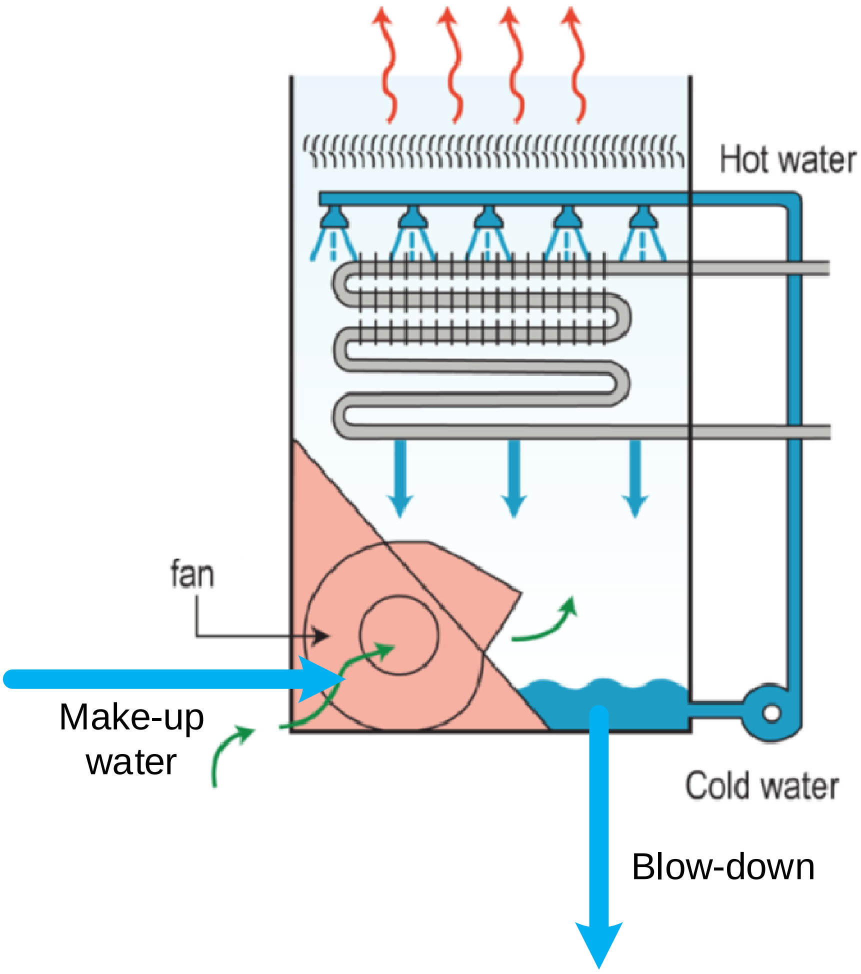

Figure 6.5. Illustration of water flow across a cooling tower.

Water quality of MEVGAL plant

Interestingly, in the case of MEVGAL plant, the blow-down water has modest TDS (due to removal of hardness salts of the make-up) as well as low organic content. In particular, total dissolved solids in the majority of the samples examined was less than 1,000 mg/L, whereas total organic carbon values were similar to those of freshwater. In addition, the absence of biocides in the cooling towers makes the blow-down water suitable for reuse. Therefore, it is considered as a valid option to collect and recycle all or part of the blow-down streams (with minimal, if any treatment), possibly for mixing with the freshwater.
It is pointed out that a detailed characterization of all blow-down streams should be performed in advance and streams with high saline content should be excluded. The recirculation of blow-down stream in MEVGAL dairy plant would reduce freshwater requirements by appr. 20% while only a small (less than 10%) increase in TDS would be recorded based on the quality characteristics in Tables 4.3 and 4.4.

7. Conclusions

For the anaerobic and aerobic MBR technologies, three alternative scenarios were developed and elaborated in a conceptual design and techno-economical evaluation.

Case 1, designed for a mixture of by-products and dilution water with a total capacity of 300 m3/day influent, delivers treated water which might be re-used in the dairy processing plant as make-up for the cooling water system. The resulting savings potential on fresh water intake is 300 m3/d, which is equivalent with a saving of 13.5%.

Compared to the base case (i.e. the current situation), the estimated savings on OPEX cost are 253 k€/yr. The total equipment cost is estimated to be 3.6 M€, including engineering and contingency cost and the resulting simple payback time is 14.2 years.

Case 2, for which the anaerobic MBR is kept the same as Case 1 and the aerobic MBR is increased in capacity to treat the anaerobic MBR effluent as well as the remaining amount of wastewater which is in Case 1 sent to the aerobic WWTP.

For this case the resulting COD content of the aerobic MBR effluent is 87mg COD/L, which might be too high for partial reuse in the cooling water system of the dairy process. In that case, all effluent has to be discharged to the local river (as is done in the base case), resulting in no savings on fresh water consumption.

Without water reuse, the saving on OPEX cost compared to the base case is 815 k€/yr. Assuming that the air compressor of the existing WWTP can be reused in this case for the aeration of the aerobic MBR, the total equipment cost amounts to 10970 k€, including engineering and contingency cost. The payback time is 13.5 years.

For **Case 3**, which is identical to case 1 but with a capacity of 500 m^3/d (instead of 300 m^3/d) for the anaerobic and aerobic MBR, the 500 m^3/d savings potential is equivalent with a 22.6% savings on the base case fresh water consumption (2216 m^3/d).
Compared to the base case, the savings on OPEX cost are 576 k€/yr. The total equipment cost for this conceptual design is determined to be 3914 k€ and the payback time 6.8 yr.

From the comparative assessment of above-mentioned 3 cases, it can be concluded that case 3 seems to be the most promising, not only because it has the lowest payback time but also because the COD level of the treated water for reuse in the cooling water system is the lowest. Additional testing is, however, recommended to ascertain that the quality of the treated water is satisfactory for the proposed reuse purposes. The forthcoming pilot testing is expected to provide such additional information.

For the **Case 4,** a submerged Ultrafiltration unit for the recovery of valuables compounds is proposed, with a nominal capacity of 40 m^3/day. Based on the preliminary analysis conducted in this deliverable, this technology is highly recommended due to its relatively low capital investment cost as well as its low operational cost. Moreover, the revenue from the concentrated recovered product is potentially high (~400k€/year). However, this value may be reduced in practice due to practical operating difficulties, inadequately researched so far. Thus, the pilot tests to be conducted in realistic environment are expected to determine potential risks and needs for improvements.

Finally, **Case 5** deals with the blow-down stream of the MEVGAL cooling towers. The most important physico-chemical parameters of such streams were determined and then they were compared with the corresponding values of fresh feed-water. Interestingly, it was concluded that blow-down water is of fair quality, and satisfactory for reuse. Therefore, it emerges as a valid option to recycle the majority of this stream, perhaps for mixing with the fresh water, after minimal if any treatment. The recirculation of blow-down water in MEVGAL dairy plant would reduce freshwater requirements by appr. 20%.

In the following Table 6.16, a comparative assessment of the various scenarios is provided in terms of savings of the main process parameters; i.e. fresh-water use and energy consumption. As outlined in the preceding concluding remarks*, case 3 scenario appears to be preferable*, because water and energy savings are significant, payback time is the smallest and the quality of treated water is satisfactory for recycling.

Table 6.16. Comparative assessment of the proposed scenarios – Summary of key process parameter values.

		Ref	Case 1		Case 2 2)		Case 3		Case 4		Case 5 3)	
Process stream	**Unit**			**Diff.** vs Ref		**Diff.** vs Ref		**Diff.** vs Ref		**Diff.** vs Ref		**Diff.** vs Ref
Fresh water	m3/d	2216	1916	-14%	1736	-22%	1716	-23%	--	0%	1832	-17%
Electricity 1)	kWh/d	73506	64792	-12%	40990	-44%	56861	-23%	418		little	
Steam 1)	t/d	--	3.1		3.1		5.2		--		--	
Biogas 1)	Nm3/d	--	1365		1484		1529		--		--	
By-products	t/d	36.5	0		0		0		2		--	
Total savings 4)	k€/yr		253		902		576		418		70	
Investment cost	k€		3,604		10,970		3,914		80		177	5)
Payback time	yr		14.2		12.2		6.8		0.2		2.5	

1) Indicated values for utility streams are only for the investigated (sub) process
2) Only recycle of the treated water as make-up for cooling water system is allowed (hygenic standards)
Assumed is that 50% of the cooling water make-up is replaced by treated water from the aerobic MBR
3) Assumed is that 80% of the cooling water blowdown of 480 m3/d is recycled (maybe only minor treatment needed)
Electricity consumptioin (for pumping) will depend on actual collecting system of blowdown water
4) Total savings of case 1 to 3 are compared to the reference case
5) Assumed is 150 k€ total equipment cost (mainly piping), with 18% additional cost for engineering and contingency

8. References

[1] A. Antony, N. Subhi, R.K. Henderson, S.J. Khan, R.M. Stuetz, P. Le-Clech, V. Chen, G. Leslie, Comparison of reverse osmosis membrane fouling profiles from Australian water recycling plants, Journal of Membrane Science, 407 (2012) 8-16.
[2] S.R. Pandey, V. Jegatheesan, K. Baskaran, L. Shu, Fouling in reverse osmosis (RO) membrane in water recovery from secondary effluent: A review, Rev. Environ. Sci. Biotechnol., 11 (2012) 125-145.
[3] V.B. Brião, C.R.G. Tavares, Effluent generation by the dairy industry: preventive attitudes and opportunities, Brazilian Journal of Chemical Engineering, 24 (2007) 487-497.
[4] World Bank (IBRD); UNEP and UNIDO, Pollution prevention and abatement handbook - Toward cleaner production in, World Bank (IBRD); UNEP and UNIDO, Washington, USA, 1998.
[5] Makisha, N., O. Saveliev, and S. Katella, Cost aspects of membrane bioreactors for wastewater treatment, IOP Conference Series: Earth and Environmental Science. Vol. 177. No. 1. IOP Publishing, 2018.
[6] C.H. Lo, E. McAdam, and S. Judd, The cost of a small membrane bioreactor, Water Science and Technology, 72 (10) (2015), 1739-1746.