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Evaluation of a membrane bioreactor regarding wastewater treatment and water reuse in the hotel sector in Uruguay

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Evaluation of a membrane bioreactor regarding wastewater treatment and water reuse in the hotel sector in Uruguay

Master of Science Thesis
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Abstract

Tourism is one of the main drivers of Uruguayan economy and in the last decade, it has been growing at an annual average rate of 6%. However, the lack of suitable infrastructure in some touristic regions has led to groundwater pollution episodes, representing a health risk to the local population and tourists.

In order to achieve a sustainable development in this sector, it is of utmost importance to preserve the natural resources by encouraging the implementation of efficient wastewater treatment technologies.

This project aimed to promote and contribute to the sustainable development of tourism in Uruguay, by studying the performance of a pilot-scale MBR for water reuse for irrigation.

The MBR pilot plant was installed in a luxurious hotel in Colonia (touristic city) and it treated 1.87 m^3 d^{-1} of medium loaded municipal wastewater. The permeate quality was evaluated for golf course irrigation and no denitrification was promoted in the reactor.

The MBR plant worked at an average flux and permeability of 11.9 $L/m^2.h$ and 73.9 $L/m^2.h.bar$ respectively. Neither sludge waste nor chemical cleaning was necessary during this two-month research. The final MLTSS concentration in the reactor was 2.8 g/L. The average operation temperature was 26.5°C, the dissolved oxygen was 3.5 mg/L and the pH was 6.54.

Total COD removal efficiencies fluctuated between 86% and 98%, being 34 mg/L the average COD concentration in the permeate. 94% was the average removal efficiency for ammonia (1.9 mg N/L in the permeate). The average total nitrogen in the permeate was 25 mg N/L. Regarding phosphorous removal, it was low (15%) and waterbody discharge standard (5 mg P/L) was not accomplished.

When comparing the permeate quality with the international standards for water reuse in restricted urban areas (EPA and WHO guidelines), all values were below the limits (Fecal Coliforms < 200 UFC/100mL).

From an agronomic point of view, the permeate presents no soil salinization risks.The permeate nutrient loads could cover 55% of the total nitrogen and 100% of the total phosphorous demand for the golf course bent grass greens (6000 m^2). Plus, all the permeate generation (6554 m^3/year) can be used for irrigation.

The investment cost of a full-scale MBR plant (32 m^3 d^{-1}) would be 120.804 USD. The operational costs were estimated in 8.623 USD (1.3 USD/m^3 of permeate). In this case of study, MBR technology was not economically feasible because the hotel's effluent already complies with the current regulation. Nevertheless, this technology could be a competitive alternative for new projects and its implementation should be promoted.

Keywords: MBR, golf course, water reuse, nutrients, hotel wastewater, organic matter.

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Table of Contents

Abstract **1**

Acknowledgments **2**

List of Figures **6**

List of Tables **7**

Abbreviations **8**

Introduction **10**
1.1. Background 10
1.2. Problem statement 10
1.3. Justification 11
1.4. Research questions 11
1.5. Research Objectives 11
1.5.1. Main objective 11
1.5.2. Specific objectives 11

Literature review **13**
2.1. Tourism sector 13
2.1.1. International approach 13
2.1.2. Uruguay approach 13
2.2. Water reuse for irrigation 14
2.2.1. Introduction 14
2.2.2. Advantages and constraints of water reuse for irrigation 15
2.2.3. Agronomic significant parameters 16
2.2.4. Human health significant parameters 16
2.2.5. Wastewater reuse for irrigation in golf courses 17
2.3. MBR technology 20
2.3.1. MBR definition 20
2.3.2. MBR advantages and disadvantages over CAS 20
2.3.3. MBR membranes 21
2.3.4. MBR fouling 21
2.3.5. MBR configuration 21
2.3.6. MBR regarding water reuse and pathogens removal 22
2.4. Water quality standards 23
2.4.1. International standards 23
2.4.2. Uruguayan standards 26

Materials and methods **28**
3.1. Pilot-scale membrane bioreactor 28

3.2. Methodology 30
3.2.1. MBR location 30
3.2.2. MBR settings before the startup 32
3.2.3. MBR startup 34
3.2.4. MBR operation 35
3.2.5. Membrane cleaning regime 36
3.2.6. Samples collection and parameters determination 36

Results and discussion 40
4.1. Influent characterization 40
4.2. MBR operational conditions 44
4.2.1. Flux and permeability 44
4.2.2. Physicochemical parameters of the aerated compartment 48
4.2.3. MLTSS and MLVSS 49
4.3. Evaluation of the MBR performance 51
4.3.1. Organic matter 51
4.3.2. Nutrients 52
4.3.3. Pathogens 55
4.4. Water quality evaluation 56
4.4.1. Permeate quality for golf course irrigation 56
4.4.2. Permeate discharge into water bodies 62
4.4.3. Comparison between permeate quality and hotel effluent quality 62
4.5. Main drawbacks of the MBR pilot system and operation 63

Economic evaluation 66
5.1. Introduction 66
5.2. Assumptions and considerations 66
5.3. Full-scale MBR costs 66
5.3.1. Capital expenditure (CAPEX) 66
5.3.2. Operation expenditure (OPEX) 67
5.4. Economic discussion 69

Conclusions and recommendations 70
6.1. Conclusions 70
6.2. Recommendations 71

References 72

Appendices 76

List of Figures

Figure 1 Major water reuse projects worldwide by Lazarova and Akiça (2005. 15
Figure 2 MBR configurations (a) sidestream MBR and (b) immersed MBR (Judd 2006). 22
Figure 3 Membranes geometries. 22
Figure 4 Pilot scale MBR components. 1- Computer connected to the PLC; 2- PLC ; 3- Compressor; 4- Reversible pump; 5- Pressure sensor; 6- Flow meter; 7- Backwash valve; 8- Inlet flow valve; 9- Aeration valve for cleaning,10-Aeration valve for fine bubble diffusor (Cunha 2015) 28
Figure 5 Pilot scale MBR valves system and control elements.1-Flow meter; 2-Pressure sensor; 3- Backwash valve; 4-Permeate valve and 5- Air valves. 29
Figure 6 MBR process diagram adapted from Cunha (2015) and modified. 29
Figure 7 Colonia location in Uruguay. 30
Figure 8 Hotel outdoor swimming pool. 30
Figure 9 Hotel golf course. 31
Figure 10 Effluent infiltration area being under maintenance. 31
Figure 11 Membrane units. 32
Figure 12 MBR transportation and location. 33
Figure 13 Replacement of the old membranes. 34
Figure 14 Hydraulic tests with clear water. 34
Figure 15 Mixed and Settled mixed liquor from the reactor on day one. 35
Figure 16 Tests kits for physicochemical analyses. 37
Figure 17 Digester and colorimeter for determining physicochemical parameters. 38
Figure 18 Part of the laboratory equipment for doing TSS and VSS. 38
Figure 19 COD concentrations in the influent. 41
Figure 20 Total P concentrations in the influent. 41
Figure 21 Total N concentrations in the influent. 41
Figure 22 Ammonia concentrations in the influent. 42
Figure 23 Influent sample 44
Figure 24 Permeate flow rate variations along the research period. 45
Figure 25 Suction pressure variations over the research period. 45
Figure 26 Leaking reversible pump 46
Figure 27 Example of 3 cycles of the membrane operation. 47
Figure 28 Membrane permeability during the research period. 48
Figure 29 MTSS and MVSS concentrations in the aerated compartment of the MBR. 50
Figure 30 Mixed Liquor last day of operation (mixed and floated). 50
Figure 31 COD concentration in the influent and permeate over the research period. 51
Figure 32 Ammonia concentration in the influent and permeate over the research period. 52
Figure 33 Phosphate concentrations. 55
Figure 34 Visual comparison between tap water (left) and the MBR permeate (right). 57
Figure 35 Irrigation water pond. 59
Figure 36 Hotel irrigation water (left) and permeate (right). 60
Figure 37 Operation costs and its components. 68

List of Tables

Table 1 Possible pathogens present in raw wastewater (US-EPA 2012). ... 17
Table 2 Main grass species used in golf courses. ... 18
Table 3 Main values for turfgrass irrigation (Landschoot). ... 18
Table 4 Nitrogen requirements for golf course grasses (Seedland). ... 19
Table 5 Mean log_{10} removals of pathogens and indicators achieved by a pilot MBR treating municipal wastewater (Ottoson et al. 2006). ... 23
Table 6 Water reuse standards according to EPA, WHO and UNEP guidelines ... 24
Table 7 Water quality according to EC and SAR values. ... 25
Table 8 Decree 253/79 standards for wastewater disposal. ... 26
Table 9 Uruguayan Irrigation Guideline (MGAP 2003). ... 27
Table 10 Operational parameters established during the research. ... 35
Table 11 Sampling point and analysis frequency. ... 38
Table 12 Influent characterization. ... 42
Table 13 MBR operational conditions. ... 44
Table 14 Pressure measurements during the research period. ... 47
Table 15 Permeability values reported for municipal wastewater pilot plants (Judd 2006). ... 48
Table 16 BOD5 concentrations in the effluent and permeate. ... 52
Table 17 Total nitrogen concentrations in the influent and permeate. ... 53
Table 18 Nitrogen composition in the permeate. ... 53
Table 19 Phosphate and COD analysis. ... 55
Table 20 Pathogen removal efficiencies achieved. ... 56
Table 21 Comparison between permeate quality and EPA water reuse standards. ... 56
Table 22 Comparison between permeate quality and Uruguay standards (2003) for irrigation. ... 57
Table 23 Comparison between permeate quality and recommended agronomic values. ... 58
Table 24 Comparison between permeate and river mean values. ... 59
Table 25 Monthly distribution of nitrogen dosage over the year. ... 61
Table 26 Monthly distribution of phosphorous dosage over the year. ... 61
Table 27 Comparison between permeate quality and Uruguayan regulations for water body discharges. 62
Table 28 Comparison between permeate and hotel effluent quality. ... 63
Table 29 Main drawbacks detected during the operation of the pilot-scale MBR. ... 64
Table 30 CAPEX calculations. ... 67
Table 31 OPEX calculations. ... 68

Abbreviations

BOD	Biological Oxygen Demand
CAS	Conventional Activated Sludge
DO	dissolved oxygen
EC	Electrical Conductivity
EPA	United States Environmental Protection Agency
FAO	Food and Agriculture Organization
FC	Faecal Colifroms
GDP	Gross Domestic Product
HRT	hydralulic retention time
MBR	Membrane Bioreactor
MLSS	Mixed liquor suspended solids
PLC	programmable logic controller
SAR	Sodium Adsorption Ratio
SCADA	supervisory control and data acquisition
SDG	Sustainable Development Goals
SRT	sludge retention time
TSS	Total Suspended Solids
UN	United Nations
UNEP	United Nations Environment Programme
UNTWO	United Nations Tourism World Organization
WHO	World Health Organization

CHAPTER 1

Introduction

1.1. Background

Uruguay has plenty of water resources and water scarcity is not a threat to the near future. Its water stress index is lower than 10% (Bordon 2017) and the amount of renewable internal freshwater resources per capita is about 28,000 m^3, almost five times the world freshwater availability (The World Bank,2014).

On the other hand, the irresponsible management of natural resources, the poorly controlled disposal of industrial and municipal wastewater and the lack of a tougher regulation, had led to a serious deterioration of the water quality. Since 2013, the government has mainly focused on recovering Santa Lucia River Basin since it provides 70% of the drinking water of the country. However, according to Kruk et al. (2013), 70% of the main water bodies in Uruguay present eutrophication and 40% have high noxious phytoplankton biomass or blooms.

Regarding the tourism industry, it has been actively growing in Uruguay and in 2015, this sector represented 7.1% of the Gross Domestic Product (GDP). Uruguay’s goal is to maintain this increase and improve the sector adopting a sustainable development. This position follows the international line promoted by United Nations Tourism World Organization (UNTWO), which has declared 2017 the international year of sustainable tourism for development.

1.2. Problem statement

In the last couple of years, several water pollution cases have arisen in the east coast of Uruguay, threatening tourism activities in one of the principal destinations of the country. In 2016, Sauce Lagoon had 25% of its surface covered by algae (2016). This problem was caused by untreated municipal wastewater discharges in the lagoon and irresponsible agriculture practices. The main serious consequence of this situation was that safe drinking water supply was compromised during high season in Punta del Este, one of the most popular seasides. Not only the water supplied was not potable, but it also had a bad odor and a dark color (2016).

Moreover, in 2017 groundwater contamination was detected in Cabo Polonio, a national protected area and one of the main natural attractions in Rocha (east coast region). Fecal coliforms and some viruses were identified in groundwater analysis, representing a health risk for the local and touristic population (2017a). According to Rocha’s council, most seasides in this region may be facing the same situation. The depletion of water resources in this area is caused by the lack of an applied environmental management plan and the lack of suitable infrastructure to receive such an amount of visitors. The main wastewater treatment facilities are septic tanks, which are not properly regulated and in summer are overloaded.

1.3. Justification

Water resources in Uruguay have been deteriorating due to uncontrolled agro-industrial activities and untreated wastewater disposals. This has affected natural attractive regions, which are a key factor of the tourism industry, one of the main drivers of Uruguayan economy.

In order to accomplish a sustainable tourism development, actions need to be taken. More efficient wastewater treatments and new water sources should be sought to prevent groundwater pollution, water scarcity and health risks.

MBR technology seems a suitable solution for the tourism sector due to its small footprint, its capacity to cope with variable loads and its reliability to provide high water quality. The potential of MBRs for water reuse makes it a promising solution for hotels since the average water consumption per capita in this sector is more than 2 times the domestic water consumption (Cremona and Saliba 2012). Furthermore, implementing a new technology that allows water reclamation improves the image of the companies among the population and visitors and follows the national and international line of achieving sustainable tourism, particularly in those hotels with high water consumption rate due to golf courses, swimming pools, and gardens.

1.4. Research questions

The following research questions were proposed to guide this project and are being answered in this report:

- How efficient is MBR technology under mild weather conditions regarding organic matter, nutrients, and pathogens removal when treating hotel blackwater?
- Does the permeate obtained comply with the required standards for water reuse for irrigation purpose?
- Is MBR technology an economically feasible alternative for the hotel sector?

1.5. Research Objectives

1.5.1. Main objective

The main objective of this research was to evaluate at pilot scale, under mild weather conditions, the performance of a membrane bioreactor-MBR regarding wastewater treatment and water reuse in the hotel sector.

1.5.2. Specific objectives

To fulfill the aim of this research, the following specific objectives are proposed:

- Establish the removal capacity of the MBR regarding organic matter, nutrients and pathogens.
- Evaluate the effluent quality for watercourse disposal and for water reuse for irrigation according to national and international standards.
- Evaluate the economic feasibility of MBR technology for the hotel sector in Uruguay.

CHAPTER 2

Literature review

This chapter presents relevant information about the topics that were addressed by this project.

2.1. Tourism sector

2.1.1. International approach

Tourism is one of the largest economic sectors in the world and has been growing by 4% every year since 2010. Regarding worldwide export earnings, tourism is the third most important category after fuels and chemicals. In 2015 it contributed almost 10% to GDP and generated 1 out of 10 jobs around the world. The tourism industry is expected to keep growing and diversifying in the next 10 years, accomplishing 1.8 billion international tourist arrivals by 2030 (UNWTO 2017a).

Plus, the United Nations Tourism World Organization (UNWTO) has declared 2017 as the 'International Year of Sustainable Tourism for Development', promoting tourism's importance concerning the following areas (UNWTO 2017b):

- Inclusive and sustainable economic growth
- Social inclusiveness, employment and poverty reduction
- Resource efficiency, environmental protection and climate change
- Cultural values, diversity and heritage
- Mutual understanding, peace and security

This declaration follows the line of the Sustainable Development Goals (SDG) created in 2015 by the United Nations (UN), in which tourism is involved in three goals: '*Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all*' (SDG 8); *'Sustainable Consumption and Production*' (SDG 12) and *'Conserve and sustainably use the oceans, seas and marine resources for sustainable development*' (SDG 14) (UNWTO 2015).

In reference to tourism main impacts, UN highlights three main issues: reduction of natural resources (water, local resources and land degradation); air, noise and water pollution and physical impacts (construction and activities that damage ecosystems) (UNEP).

2.1.2. Uruguay approach

Tourism in Uruguay contributes 7.1% to GDP (2015) and is the main source of foreign currency. In the last decade, this sector has been growing at an average rate of 6% every year. Whereas in 2006 the number of visitors represented 53% of Uruguayan population, last year the country received 3,328,450 people (98% of its population) (URUGUAYXXI 2017).

The main natural highlights of the country are its ocean coast with white sand beaches and its wide rural areas. Urban tourism is also popular, being Montevideo, Punta del Este, Salto and Colonia the most visited cities (URUGUAYXXI 2017).

Uruguay natural attractions have been actively promoted through the publicity campaign 'Uruguay Natural' (URUGUAYXXI 2017). Investment national policies have also encouraged the development of the sector and in the last decade more than 1,500 millions USD were invested in the hotel industry (Puig 2017). These investments should preserve the location, protect the environment and create opportunities for sustainable growth (URUGUAYXXI 2017).

Uruguay's tourism goal is to keep expanding and improving the sector following the line of the national program 'Sustainable Tourism National Plan 2009-2020', created in 2009 by the Ministry of Tourism and Sports. The aim of this plan is to achieve a responsible tourism management and development, capable of promoting social equality and a sustainable use of natural resources (MINTURD 2009). Regarding the environment, the plan proposes the following specific objectives:

- Plan the tourism development considering the natural and cultural resources, paying special attention to the national protected areas and heritage sites.
- Study the impact of the investments on the economy, the environment and the society.
- Control the investments through a responsible tourism management taking into account the load capacity of the destinations.
- Promote and support the use of renewable resources and eco-friendly technologies.

Since 2017, the Ministry of Tourism and Sports is also working with the private sector on a pilot project called 'Green Seal', to encourage the tourism sustainability and to address global warming concerns (2017b).

2.2. Water reuse for irrigation

2.2.1. Introduction

As the global population increases, there is more pressure on water resources and water reclamation becomes an attractive solution, especially to water scarce regions or densely populated urban areas (Verrecht et al. 2012). The main drivers for water reuse are the preservation of freshwater sources, the lack of sewage and in metropolitan areas, the approach of building more sustainable cities.

Water reuse for irrigation is a worldwide practice, particularly popular in Mediterranean region and United States (Figure 1):

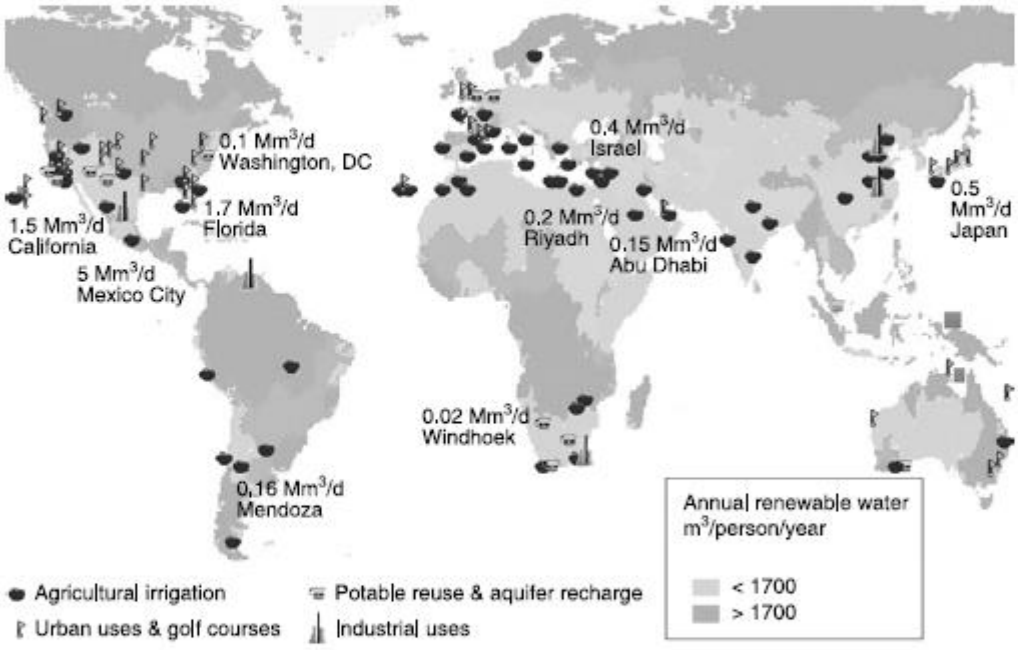

Figure 1 Major water reuse projects worldwide by Lazarova and Akiça (2005**.**

According to US-EPA (2012), 32.01% of the global water reuse (with tertiary treatment) goes to agricultural irrigation and 20% goes to landscape irrigation. Then it comes the industry sector, representing 19.3% of the global water reuse.

2.2.2. Advantages and constraints of water reuse for irrigation

According to Lazarova and Akiça (2005), the main advantages of water reuse for irrigation are:

- Provide a reliable and secure water source, even in drought periods
- Close the water cycle
- Save high-quality freshwater for potable water supply
- In areas with no sewage prevent environmental pollution and public health risks
- Reduce commercial fertilizers uses
- Improve tourism activities in dry regions
- Promote a sustainable development

Regarding the major drawbacks and challenges of this practice, Lazarova and Akiça (2005) mentions:

- Health risks due to pathogens or chemicals if water reclamation is implemented inadequately
- Social acceptability for reuse water
- Cost of recycled water infrastructure
- Possible need for large storage capacity

- Potential negative impact on soil and crops due to boron and salts present in wastewaters
- The implementation may not be economically feasible due to cheap water prices and lack of regulations and incentives for water reclamation

2.2.3. Agronomic significant parameters

When irrigating green areas, landscapes and turf grass fields, the main agronomic parameters to consider are salinity, toxic ions, Sodium Adsorption Ratio (SAR), pH, chloride, bicarbonate and carbonate and nutrients (Lazarova and Akiça 2005).

Water salinity is measured by Total Dissolved Solids (TDS, mg/L) and Electrical Conductivity (EC, dS/m). When irrigation comes from reclaimed domestic wastewater, these parameters are rarely a major concern and, as a rule, recycled urban water salinity is below 2 dS/m (slightly saline water). Salinity may be a threat in coastal areas, where saline infiltration into the sewer system may occur (Lazarova and Akiça 2005).

Regarding toxic ions in domestic wastewater, the most common ones are boron, chloride, and sodium (Lazarova and Akiça 2005).

Sodium is an important cation because it can modify the soil structure, affecting its water infiltration capacity. The SAR can be calculated in mEq/L as:

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}}$$

Water with SAR values below 3 is a safe irrigation source, but if SAR is higher than 9, soil deterioration may occur. Considering the link between sodium concentration and salinity, SAR and EC parameters are usually compared together to evaluate the potential risks of irrigation water (Lazarova and Akiça 2005).

Nitrogen and phosphorous are essential macronutrients for grass and crops growth. However, if nitrogen input into the soil is excessive, nitrates may move to groundwater streams. In order to prevent their contamination, when irrigating with domestic treated wastewater, nitrogen concentrations should be monitored (Lazarova and Akiça 2005).

In the case of phosphate ions, high concentrations may affect copper and zinc mobility through the soil. Yet, the phosphate content in domestic wastewater is usually lower than soil requirements and external phosphate fertilizers may be needed (Lazarova and Akiça 2005).

2.2.4. Human health significant parameters

Enteric pathogens are those microorganisms that live in humans or animals intestines and are generally transmitted by being in contact with feces, by eating contaminated food or by drinking contaminated water. Domestic wastewater is a potential source of infection that can contain a large number of pathogens excreted mostly by infected individuals (Henze et al.

2008). Helminths eggs (worm eggs) can also be found in domestic wastewater and infect human beings.

Table 1 presents common enteric pathogens that can be found in raw wastewater, its maximums concentrations and the diseases they cause.

Table 1 Possible pathogens present in raw wastewater (US-EPA 2012).

Type	Pathogen	Disease	N° in Raw Wastewater per lite
Bacteria	Shigella	Shigellosis	Up to 10^4
	Salmonella	Salmonellosis, gastroenteritis, etc	Up to 10^5
	Campylobacter	Gastroenteritis, reactive arthritis, etc	Up to 10^4
Protozoa	Giardia	Giardiasis (gastroenteritis)	Up to 10^5
	Cryptosporidium	Crystosporidiosis, diarrhea,fever.	Up to 10^4
Viruses	Enteroviruses	Gastroenteritis,heart anomalies,meningitis, etc.	Up to 10^6
	Rotavirus	Gastroenteritis	Up to 10^5
	Caliciviruses (including Norovirus and Sapovirus)	Gastroenteritis	Up to 10^9

According to WHO (2006), the exposure route of these pathogens can be by contact or by consumption. Therefore, secondary treatment and further disinfection are essential when irrigating crops that are eaten raw or when irrigating recreational areas where the population can be in touch with the water source (WHO 2006).

The international guidelines for safe water reuse are presented at the end of this chapter (Table 6 **Water reuse standards according to EPA, WHO and UNEP guidelines**.Table 6).

2.2.5. Wastewater reuse for irrigation in golf courses

Introduction to golf courses

When designing a golf course, a key factor to take into account is the selection of a suitable type of grass based on the soil and weather conditions of the region, water availability and the area of the golf course (teens, green, hazards or fairways) (Barber). In general, the grass species selected are resilient, fast repairing grasses that can tolerate a lot of traffic (golfers, trolleys and carts) (Chi).

The most popular turf grasses used for golf course design are mentioned in Table 1:

Table 2 Main grass species used in golf courses.

Commercial name	Species name	Main features	Main Uses	Source
Bentgrass	Agrostis Stolonifera	- Withstands poor water quality and high salinities, but is not tolerant to water stress and lack of sunlight. - Suitable for loose soils and coastal locations	Greens	(Golfparatodos.es)
Bermuda grass	Cynodon dactylon	-Robust species, tolerant to salinity, droughts and high temperatures. Requires a lot of sunlight -Highly recommended for warm weather conditions.	Tees, fairways and greens	(Golfparatodos.es) (Golf SC)
Ryegrass	Lolium Perenne	-Cool weather species (12-24°C) very tolerant to traffic but highly demanding on water and nitrogen	Tees and fairways	(Golfparatodos.es) (Golf World Directory 2017)
Zoysias	Zoysias	-Versatile species, adaptable to warm or cool weather -Very resistant to traffic but presents slow recovery	Tees, greens and fairways	(Golf World Directory 2017) (Golfparatodos.es)

Regarding Uruguay, the most spread species used in local golf courses are Bentgrass for greens and Bermuda for fairways and tees.

Golf course irrigation requirements

Table 3 Table 3reports recommended values for the main agronomic parameters for turfgrass irrigation according to Landschoot:

Table 3 Main values for turfgrass irrigation (Landschoot).

Parameters	Recommended values
pH	6-7
Bicarbonate (mg/L)	<120
EC (Ds/m)	0,31-0,78
Na (mg/L)	<70
SAR	<9

Parameters	Recommended values
Chloride (mg/L)	<100
Boron (mg/L)	<2

Regarding nutrients requirements, Table 4 presents the nitrogen demand for each type of grass:

Table 4 Nitrogen requirements for golf course grasses (Seedland).

Type	kg N/year/100 m^2
Bentgrass	1,5-3,0
Ryegrass	1,0-2,4
Bermuda	1,0-2,4
Zoysia	1,0-2,0

In regions where warm seasons are longer and winters are not harsh, the upper values of each range should be used (The National Gardening Association).

When it comes to phosphorous and potassium inputs, Busso (2012) reports that 5:1:5 is a commonly used N:P:K ratio in golf courses.

Reusing wastewater in golf courses

Hundreds of golf courses around the world have implemented water reclamation within their facilities; especially in the Mediterranean region and the United States (Lazarova and Akiça 2005).

In Tunisia, secondary treated wastewater has been being used for twenty years, without showing any adverse effect on the turfgrass development (Lazarova and Akiça 2005).

On the other hand, Qian and Mecham (2005) reported that golf courses irrigated with recycled wastewater presented 187 % higher EC and 481% higher SAR than those sites irrigated with surface water. Moreover, significant accumulation of sodium, boron and phosphorous was observed in the fairways irrigated with the recycled wastewater.

Candela et al. (2007) also reported soil salinization in a golf course in Spain that has been irrigated with treated urban wastewater for ten months. Regarding pathogens content in the soil and groundwater, no microbiological risks were detected.

According to Chen et al. (2015), water reclamation in green urban areas in China also increased EC and SAR values of the soil. However, no significant accumulation of heavy metals was observed. Regarding soil microbiological activity, Chen et al. (2015) mentions that it could be improved by the use of treated wastewater due to its inputs of biodegradable organic matter and nutrients.

To address the potential risks of soil salinization and sodium accumulation, Chen et al. (2013) suggested the following measures:

- provide a suitable leaching fraction, especially on golf course greens,
- select an adequate irrigation method,
- add gypsum or lime to amend the soil,
- install efficient drainage systems,
- choose salinity tolerant plant species and
- blend irrigation water with water streams with lower SAR and EC.

Other recommendations proposed by Lazarova and Akiça (2005) for achieving a successful and safe golf course irrigation are:

- have an emergency water source in case the effluent does not accomplish the water qualities
- install a separated pipeline for the reused water and distinguish it with a color code or sign
- balance fertilization talking into account the nutrients input of the effluent
- inform the golfers that the irrigation water is non-potable, by using warning signs
- design storage units with a minimum hydraulic retention time of one day (golf course watering is done at night)
- control soil moisture and daily evapotranspiration with on-site instrumentation.

2.3. MBR technology

2.3.1. MBR definition

Membrane bioreactors combine a conventional activated sludge (CAS) treatment with membrane filtration for biomass retention (Judd 2006). In one unit, four main steps of a conventional wastewater treatment plant are efficiently achieved: primary settling, biological degradation of pollutants, secondary settling and disinfection (Henze et al. 2008).

2.3.2. MBR advantages and disadvantages over CAS

According to Melin et al. (2006), the main advantages of MBR over CAS are:

- Smaller footprint, as MBR reactors work with higher concentrations of mixed liquor total suspended solids (MLTSS) and loading rates.
- Reduced sludge production.
- Uncouple hydraulic retention time (HRT) from sludge retention time (SRT), allowing a more flexible control over operating parameters.
- Production of consistently clear and high-quality effluent, with a considerable removal of pathogens.
- Lower sensitivity to contaminant peaks.
- Development of specialized, slow-growing microorganisms with potential for improving recalcitrant compounds degradation.

On the other hand, García (2017) mentions the following disadvantages for MBRs:

- Greater process complexity
- Membrane surface fouling
- Membrane channel clogging
- Higher capital equipment and operating costs

2.3.3. MBR membranes

Microfiltration (100-1000 nm) or ultrafiltration membranes (5-100 nm) are used since they offer sufficient rejection and reasonable fouling control. Regarding membrane material, chemically and mechanically strong polymers are selected, as they can resist the stresses imposed during filtration and cleaning cycles. Plus, membrane surfaces are modified to provide a hydrophilic exterior (less susceptible to fouling than hydrophobic materials) (Judd 2006). Most common selected polymers are (i) polyvinylidene difluoride (PVDF), (ii) polyethylsulphone (PES), (iii) polyethylene (PE) and (iv) polypropylene (Henze et al. 2008).

2.3.4. MBR fouling

One of the main constraints of MBRs is membrane fouling, a decrease in the permeate flux caused by the interactions between the membrane and the compounds in the mixed liquor.

According to Barceló and Petrovic (2008), the main causes of membrane fouling are:

1. adsorption of macromolecular and colloidal matter,
2. the growth of biofilms on the membrane surface,
3. precipitation of inorganic matter and
4. aging of the membrane.

From a practical approach, fouling can be classified in

- Reversible or temporary: can be removed by physical cleaning.
- Irreversible or permanent: needs chemical cleaning.
- Absolute: cannot be removed by any cleaning regime

2.3.5. MBR configuration

Depending on the integration of the membrane with the reactor and hydraulic operation, there are two main configurations: side-stream MBRs with pressure-driven filtration or immerse membranes in the bioreactor with vacuum-driven separation (Figure 2). The latter configuration is more common for wastewater treatment and requires significantly less energy than side-stream MBRs (Barceló and Petrovic 2008). To prevent membrane fouling, side-stream MBRs induce turbulence by pumping, whereas immersed systems employ aeration (Barceló and Petrovic 2008).

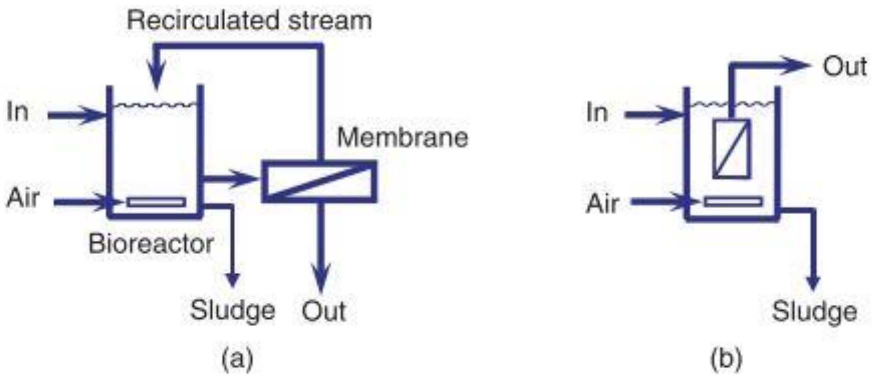

Figure 2 MBR configurations (a) sidestream MBR and (b) immersed MBR (Judd 2006).

There are also three predominant membrane geometries: flat sheet, hollow fiber and multitube (Figure 3).

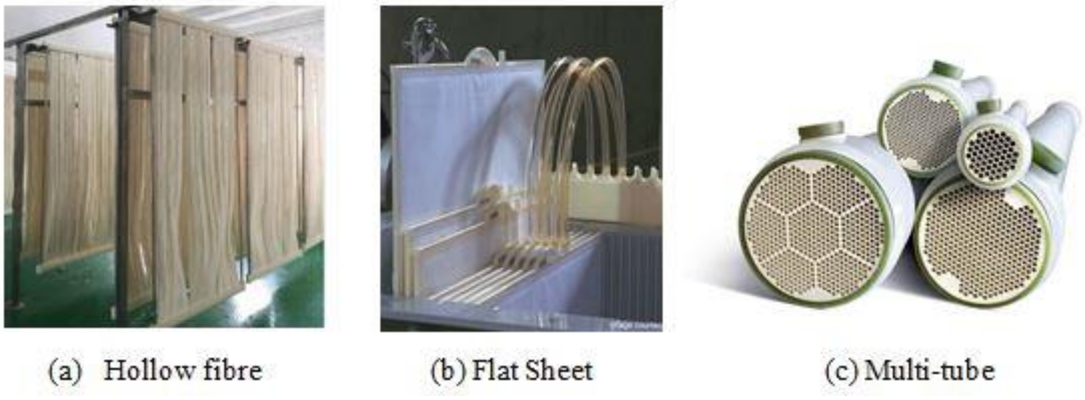

Figure 3 Membranes geometries.

2.3.6. MBR regarding water reuse and pathogens removal

When it comes to water reuse, MBR technology is a technically feasible alternative, as it guarantees consistently high-quality effluent and has a small footprint (Atanasova et al. 2017). Furthermore, MBR capacity for coping with variable loads, seasonally and diurnally, makes it an especially suitable solution for the tourism sector (Verrecht et al. 2012).

Several studies have been conducted in hotels, sports centers and small communities regarding greywater and domestic wastewater reuse for flushing the toilet, irrigation or cleaning. High organic matter removal efficiencies were achieved (around 90%), complying in each case with the required standards ((Merz et al. 2007; Paris and Schlapp 2010; Verrecht et al. 2012; Santasmasas et al. 2013; Atanasova et al. 2017). According to Merz et al. (2007), when using MBR for treating shower effluents, the water obtained has an excellent aesthetic quality. However, for blackwater reuse, further treatment is needed to remove odor and color (Verrecht et al. 2012).

Regarding pathogens reduction, Atanasova et al. 2017 and Bolzonella et al. (2010) reported between 3-5 and 4-5 log_{10} total coliform removal. Concerning virus concentrations, Sano et al. (2016) informed 3.35 log_{10} reduction for norovirus GII and 2.71 log_{10} reduction for enterovirus. Table 5 presents some indicator and pathogen log_{10} removals reported by Ottoson et al. (2006).

Table 5 Mean log_{10} removals of pathogens and indicators achieved by a pilot MBR treating municipal wastewater (Ottoson et al. 2006).

Organism	log_{10} removal
Escherichia Coli	4,97
Enterococci	4,52
Somatic coliphages	3,08
F-specific coliphages	3,78
Enteroviruses	1,79
Giardia cysts	>3,52
Cryptosporidium oocysts	>1,44

To prevent bacterial regrowth in pipelines or avoid any health risk, further disinfection is required (Merz et al. 2007; Bolzonella et al. 2010; Friedler and Gilboa 2010; Verrecht et al. 2012; Santasmasas et al. 2013; Atanasova et al. 2017). Since organic matter and suspended solids content is negligible in MBR effluent, UV radiation is an effective and efficient posttreatment (Barceló and Petrovic 2008; Friedler and Gilboa 2010).

2.4. Water quality standards

2.4.1. International standards

When it comes to water reuse and reclamation, the World Health Organization (WHO) and the United States Environmental Protection Agency (US-EPA) are well-known references which have been working on the subject since 1973 and 1980 respectively (WHO 2006; US-EPA 2012). The latest WHO and US-EPA publications regarding safe wastewater management are ‘WHO guidelines for the safe use of wastewater, excreta, and greywater’ (2006) and ‘2012 Guidelines for water reuse’ respectively. In 2005 the United Nations Environment Programme (UNEP) also published ‘Guidelines for municipal water reuse in the Mediterranean region’. Table 6 summarises the water quality parameters and the limits recommended by these institutions in order to prevent health and environmental risks.

Table 6 Water reuse standards according to EPA, WHO and UNEP guidelines.

		EPA		WHO		UNEP	
	Parameters	**Limit**	**Monitoring**	**Limit**	**Monitoring**	**Limit**	**Monitoring**
Unrestricted urban areas Municipal settings where public access is not restricted, e.g. public parks, hotel lawns.	pH	6-9	Weekly	-	-	-	-
	BOD_5 (mg/L)	≤10	Weekly	-	-	-	-
	Turbidity (NTU)	≤2	Continuous	-	-	-	-
	TSS(mg/L)	-	-	-	-	≤10	-
	Faecal Coliform (UFC/100mL)	No detectable	Daily	≤200	Twice a month	≤200	Weekly
	Intestinal Nematodes (N°/L)*	-	-	≤1	Monthly	≤0,1	Once
	Cl2 residual (mg/L)	1	Continuous	-		-	-
Restricted urban areas Municipal settings where public access is controlled or restricted by physical or institutional barriers, such as fencing, advisory signage.	pH	6-9	Weekly	-		-	-
	BOD_5 (mg/L)	≤30	Weekly	-		-	-
	Turbidity (NTU)	-	-	-		-	-
	TSS(mg/L)	≤30	Daily	-		≤10	-
	Faecal Coliform (UFC/100mL)	≤200	Daily	≤1000	Twice a month	≤200	Weekly
	Intestinal Nematodes (N°/L)*	-	-	≤1	Monthly	≤0,1	Once
	Cl2 residual (mg/L)	1	Continuous	-	-	-	-
Food crop irrigation Surface or spray irrigation of food crops which are intended for human consumption consumed raw	pH	6-9	Weekly	-	-	-	-
	BOD_5 (mg/L)	≤10	Weekly	-	-	-	-
	Turbidity (NTU)	≤2	Daily	-	-	-	-
	TSS(mg/L)	-	Daily	-	-	≤20*	-
	Faecal Coliform (UFC/100mL)	No detectable	Daily	≤1000	Monthly	≤1000	Weekly
	Intestinal Nematodes (N°/L)*	-	-	≤1	Every 1-2 months	≤0,1	Once
	Cl2 residual (mg/L)	1	Continuous				-

	Parameters	EPA Limit	EPA Monitoring	WHO Limit	WHO Monitoring	UNEP Limit	UNEP Monitoring
Processed food crop and non-food Crop irrigation	pH	6-9	Weekly	-			-
	BOD (mg/L)	≤30	Weekly	-			-
	Turbidity (NTU)	-	-	-			-
	TSS(mg/L)	≤30	Daily	-		≤35*	-
	Faecal Coliform (UFC/100mL)	≤200	Daily	-	Monthly	≤105	Weekly
	Intestinal Nematodes (N°/L)*	-	-	≤1	Every 1-2 months	≤1	Once
	Cl2 residual (mg/L)	1	Continuous	-			-

According to US-EPA (2012) water reclamation for unrestricted urban areas should also be odorless and colorless.

The Food and Agriculture Organization (FAO) also proposes an irrigation guideline for agriculture which is mainly focused on soil preservation and crops productivity. Regarding turfgrass irrigation, the main parameters to be controlled are electrical conductivity (EC) and Sodium Adsorption Ratio (SAR), as they affect soil salinity and water infiltration rate (Ayers and Westcot 1985) Table 7 presents water classification according to these parameters.

Table 7 Water quality according to EC and SAR values.

			Degree of Restriction on Use		
			None	**Slight to Moderate**	**Severe**
SAR (meq/L)=	0-3	**and EC (dS/m)**	>0,7	0,7-0,2	<0,2
	3-6		>1,2	1,2-0,3	<0,3
	6-12		>1,9	1,9-0,5	<0,5
	12-20		>2,9	2,9-1,3	<1,3
	20-40		>5	5-2,9	<2,9

2.4.2. Uruguayan standards

The national institution in charge of environmental management and regulations is The Ministry of Housing, Territorial Planning and Environment (MVOTMA). Under its supervision, it works the National Environmental Agency (DINAMA), responsible for creating and applying national environmental programs as well as controlling company's wastewater and solid wastes discharges.

The Decree 253/79, created in 1979 by DINAMA and approved by the Government, establishes the water quality standards required for waterbodies and wastewater discharges. Depending on the final disposal, different parameters and limits are proposed. Field infiltration and watercourse discharge limits relevant to this project are presented in Table 8.

Table 8 Decree 253/79 standards for wastewater disposal.

	Water Course	Field Infiltration
Floating material and foam	None	-
Temperature (°C)	<30	-
pH	6-9	6,5-8,5
TSS (mg/L)	150	-
BOD5	60 (mg/L)	50 Kg DBO5/Ha/d
Fats and Oils (mg/L)	40	200
Anionic Surfactant (mg/L)	4	-
Non Ionic Surfactant(mg/L)	4	-
Total Phosphorous (mg P/L)	5	-
Total Kjeldahl Nitrogen (mg N/L)	10	-
Ammonia (mg N/L)	5	-
Nitrate (mg N/L)	20	-
Sulfide (mg/L)	1	-
Thermoresistant Coliforms (UFC/100mL)	5000	-
Phenols (mg/L)	0,5	0,5

Regarding water quality for irrigation, there is a national guideline provided in 2003 by the Ministry of Cattle Raising, Agriculture and Fishing (MGAP). Depending on the concentration of certain parameters (Table 9), MGAP (2003) classifies the water into three categories:

- Class 1: water is OK and no further information is required
- Class 2: an irrigation plan including possible negative impacts of the water in the soil should be presented to the MGAP

- Class 3: it is compulsory to present to MGAP an irrigation plan including the morphological description of the soil profile and a physicochemical analysis of A horizon.

Table 9 Uruguayan Irrigation Guideline (MGAP 2003).

	Class 1	Class 2	Class 3
EC (mS/cm)	<2	2-3	>3
pH	-	-	>8,5
SAR (meq/L)	<6	6-10	>10
Bicarbonate ($CaCO_3$) (mg/L)	<250	>250	-
Chloride (mg/L)	<150	150-300	>300

CHAPTER 3

Materials and methods

3.1. Pilot-scale membrane bioreactor

The pilot-scale membrane bioreactor was provided by Almes-eko Company in 2014 for a research study on dairy effluents in Uruguay. In 2015, under another research project, the performance of the system was evaluated in the slaughterhouse sector. The latest MBR application was last year, treating wastewater from a dairy farm.

The pilot MBR is a compact unit made out of stainless steel and has a treatment capacity of 1 m^3d^{-1}. The reactor was designed for a MLSS concentration between 8 and 12 g/l and for constant membrane flux operation.

The bioreactor consists of two compartments, the de-nitrification (anoxic) and the nitrification (aerated) part. Inside the latter it is installed a fine bubble diffusor, a recirculation pump, the membrane scour system (coarse bubble diffusor) and the submerged membranes, which are connected to the aeration and permeate pipelines. The membranes have a 6.6 m^2 ultrafiltration surface (average pore size 0.4 µm) and have a multitube configuration. Other elements of the system are an air compressor, influent, recirculation and permeate pumps and a programmable logic controller (PLC) with supervisory control and data acquisition (SCADA) software. and Figure 5 show the MBR equipment and its elements in detail.

Figure 4 Pilot scale MBR components. 1- Computer connected to the PLC; 2- PLC ; 3- Compressor; 4- Reversible pump; 5- Pressure sensor; 6- Flow meter; 7- Backwash valve; 8- Inlet flow valve; 9- Aeration valve for cleaning,10-Aeration valve for fine bubble diffusor (Cunha 2015)

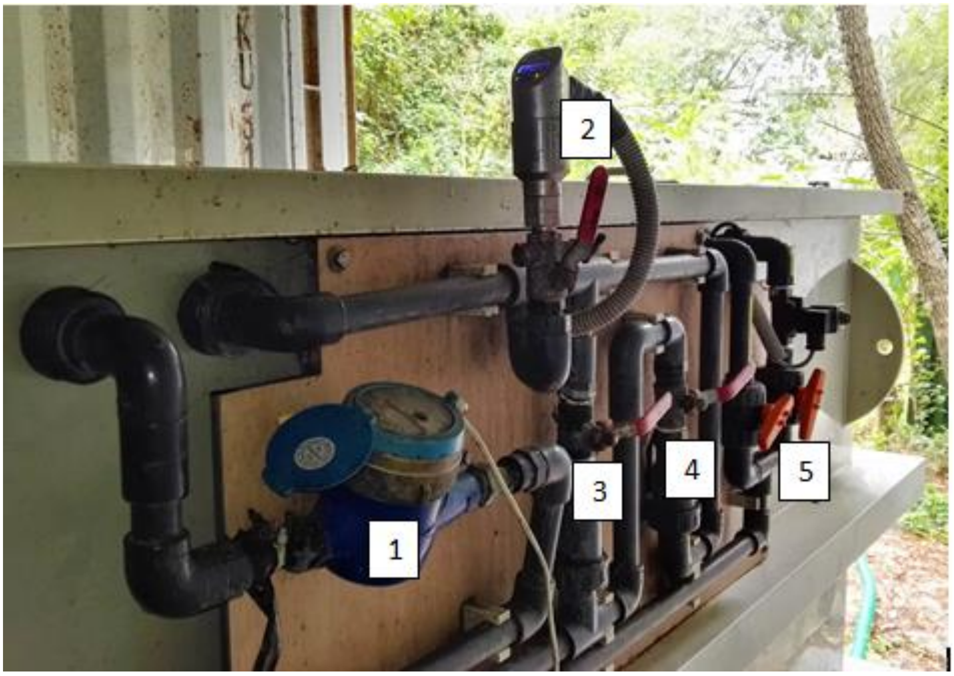

Figure 5 Pilot scale MBR valves system and control elements.1-Flow meter; 2-Pressure sensor; 3-Backwash valve; 4-Permeate valve and 5- Air valves.

The treatment process begins with pumping the influent into the anoxic compartment. Then the liquid overflows to the nitrification zone where membrane filtration occurs. The effluent is sucked out by a reversible pump and carried to the permeate basin. Once this tank is full, the water is discharged by overflow through a 1" pipe. The membranes are backflushed with the effluent, using the reversible pump. Waste sludge is removed from the system using the recirculation pump in combination with the corresponding valve. The recirculation pump is also used to achieve denitrification in the anoxic chamber.
Figure **6** illustrates the process flow diagram of the typical MBR pilot plant when nitrification and denitrification are required.

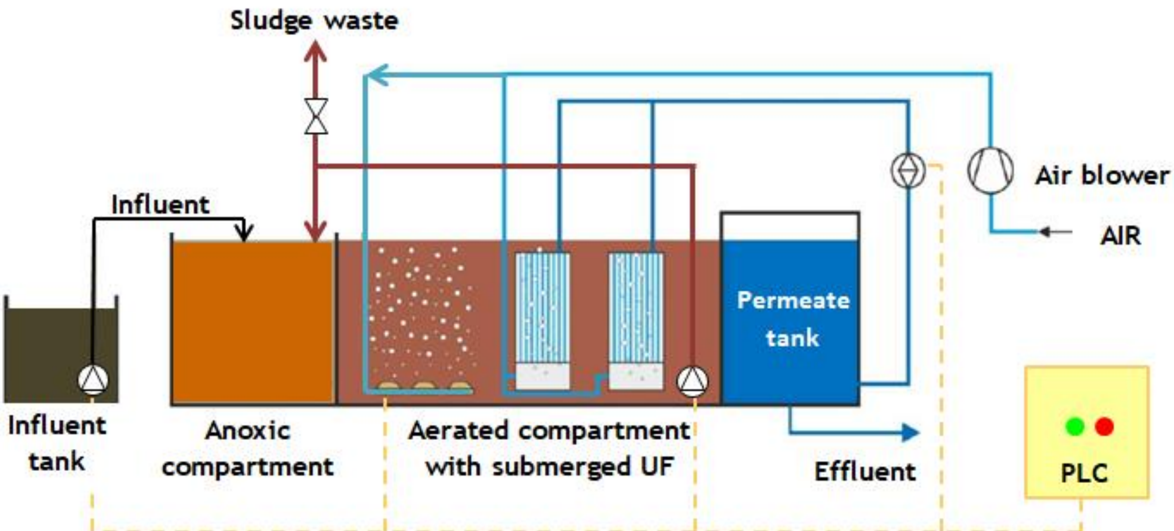

Figure 6 MBR process diagram adapted from Cunha (2015**)** and modified.

3.2. Methodology

3.2.1. MBR location

The reactor was installed in a hotel located in Colonia department, south-west coast of Uruguay and one of the most touristic regions in the country (Figure 7). The main attractions of the hotel are its large golf course, its outstanding spa and the relaxing and natural surroundings (
Figure 8 and
Figure 9).

Figure 7 Colonia location in Uruguay.

Figure 8 Hotel outdoor swimming pool.

Figure 9 Hotel golf course.

In 2017, the hotel received around 40,500 visitors. and the daily water consumption per capita was 265 litres. Regarding the wastewater generation, 6455 m^3 were discharged by infiltration, which represents 60% of the hotel drinking water consumption. The water demand for gardens and golf course irrigation can be up to 15,000 m^3/month and is taken from a pond that mainly storages rainwater and runoffs.

The current wastewater treatment plant of the hotel consists of a septic tank followed by a CAS system. After the septic tank, the water overflows to another compartment that works as an equalization tank. Then it comes the biological aerated treatment with a secondary settler. The effluent is infiltrated in a surrounding area of 110 m^2 designated for that purpose and restricted to visitors (Figure 10). The sludge waste is stored in the septic tank, which is cleaned twice a year by a sludge truck that discharges the sludge in the local sewer system.

Figure 10 Effluent infiltration area being under maintenance.

The MBR pilot system was located after the equalization tank, so to receive the same wastewater as the biological aerated tank of the hotel.

3.2.2. MBR settings before the startup

After choosing the MBR location, the first step was moving the MBR pilot plant from Anchorena's farm (previous working place) to the hotel. Before its transportation, the MBR was emptied and membrane units were removed to make the system lighter (¡Error! No se encuentra el origen de la referencia.**). To ensure its proper operation and keep it safe from weather conditions, the reactor was placed inside a standard container (**

Figure 12)

Figure 11 Membrane units.

Figure 12 MBR transportation and location.

Other tasks required before operating the MBR were:

- the connection of the PLC control panel and the influent pump to the power supply,
- installation of a retention valve in the inlet pipeline of the pilot system to prevent the reactor being emptied by differential pressure,
- installation of a new valve in the sludge pipeline of the hotel wastewater treatment plant to help to the inoculation of the MBR
- the connection of a hose to the permeate pipeline to avoid the formation of puddles in the surroundings of the reactor and inside the container
- air purgation of the permeate pipeline to prevent the damage of the reverse pump and replacement of old membranes units by new ones (
- **Figure 13**)

Once the new membranes were connected, the reactor was filled with clear water and hydraulics tests were made to check the pumps and possible leaks in the air and permeate pipelines (Figure 14).

Figure 13 Replacement of the old membranes.

Figure 14 Hydraulic tests with clear water.

After that, the membranes were activated working in backwash mode for 30 minutes at a pressure of 0.11 bar. Then, the membranes worked with vacuum pressure (-0.11 bar) for another 30 minutes.

3.2.3. MBR startup

The 4th of January the reactor was fed with raw wastewater and the permeate and backwash valves were regulated to achieve an absolute value pressure of 0.11 bar. The initial flow rate was around 2.5 m^3d^{-1}; 2,5 times higher than the designed one. However, to prevent the damage of the reverse pump, lower pressures and flow rates could not be set. A visual control of the obtained permeate was done to check that the membranes were properly replaced.

The 5th of January the reactor was inoculated with 160 L of sludge coming from the bottom of the secondary settler of the treatment plant. Unfortunately, the sludge was septic and had a low content of solids, so the initial concentration of total suspended solids (TSS) achieved in the reactor was only 419 mg/L. A mixed and settled sample of the mixed liquor on day one can be seen in
Figure 15, showing the low solid content in the mixed liquor.

Figure 15 Mixed and Settled mixed liquor from the reactor on day one.

The reactor was operated in manual mode for three days and the 8th of January continuous operation started. However, in order to increase the TSS concentration in the reactor, no sludge waste was done during the whole research period (two months):

3.2.4. MBR operation

After the startup, the MBR was automated via a PLC integrated with a SCADA system that registered pressure and flow rate values. However, to turn on the system and to regulate the air, permeate and backwash valves, a manual operation was required.

Main MBR control parameters set on the PLC are shown in Table 10 **Operational parameters established during the research.**Table 10.

Table 10 Operational parameters established during the research.

Parameter	Value	Comments
Recirculation flow/permeate flow	0.05	The PLC did not allow turning off the recirculation pump
Filtration time (min)	10	-
Backwash time (min)	1	-
Max. pressure during backwash (mbar)	400(overpressure)	-

Max. Pressure during filtration (mbar)	400 (vacuum)	-

To achieve maximum nitrification, the fine bubble diffuser was working full time. On the other hand, to prevent denitrification, the recirculation pump operation was minimized.

Considering that no phosphorous standards are established for irrigation, phosphorous removal was not enhanced by further treatments.

The MBR was operated for two months (January-February).

Detailed information of the MBR operational conditions can be found in Chapter 4.

3.2.5. Membrane cleaning regime

Since the maximum suction pressure acceptable by the membranes was never reached (- 400 mbar), there was no need of doing a chemical cleaning of the units. If that had not been the case, and if the maximum pressure had been exceeded, the membranes would have been backwashed for 30 minutes with a 500 ppm Sodium Hypochlorite solution.

3.2.6. Samples collection and parameters determination

To evaluate the performance of the pilot MBR, the following parameters were analyzed in the influent and effluent streams:

- ✓ Total Chemical Oxygen Demand (COD)
- ✓ Nitrate (NO_3^-)
- ✓ Nitrite (NO_2^-)
- ✓ Ammonia (NH_4^+)
- ✓ Total Nitrogen (TN)
- ✓ Phosphate (PO_4^{3-})
- ✓ Total Phosphorous (TP)
- ✓ Total Biological Oxygen Demand after 5 days (BOD_5)
- ✓ E.Coli
- ✓ Fecal Coliforms (FC)
- ✓ Total Coliforms (TC)
- ✓ Temperature (T)
- ✓ pH

Soluble COD and BOD_5, soluble TN, soluble TP and TSS were also analysed in the influent for its characterization.

Due to laboratories delays, Kjeldahl Nitrogen (TKN) was only analysed once in the influent and permeate results could not be obtained.

Regarding the permeate quality for irrigation, analysis of turbidity, electrical conductivity (EC), bicarbonate, chloride, residual chlorine and boron were done.

Calcium, magnesium and sodium were supposed to be done as well, but due to a misunderstanding with the laboratory's staff, it was only analyzed once and in the influent.

To check the permeate quality for water bodies discharge, sulphide and anionic surfactant concentrations were evaluated.

Inside the mixed liquor compartment, pH, temperature, TSS and VSS were weekly analyzed. Dissolved Oxygen (DO) in the reactor was only checked twice over this research period, due to the availability of a handheld oxygen meter (GPS Aquameter).

Two samples of the current hotel effluent and the water stream that the hotel is using nowadays for golf course irrigation were also taken to compare their features with the ones of the MBR permeate.

The parameters that were analyzed on the field were temperature, pH, DO and EC.

The analyses of COD, NO_3^-, NO_2^-, NH_4^+, TN, TP, and PO_4^{3-} were carried out with a Spectroquant® Move 100 colorimeter and its test kits provided by LATITUD (**Figure 16** and Figure 17).

The solid content analyses were done according to "Standard Methods for the Examination of Water and Wastewater, 1999", using the stove, muffle and small vacuum filter available in LATITUD laboratories (Figure 18).

The other parameters were analyzed by LATU laboratories.

Figure 16 Tests kits for physicochemical analyses.

Figure 17 Digester and colorimeter for determining physicochemical parameters.

Figure 18 Part of the laboratory equipment for doing TSS and VSS.

Table 11 summarises the sampling collection the methodology used:

Table 11 Sampling point and analysis frequency.

Parameters	Sampling Point					
	Unit	**Influent**	**Permeate**	**Aerated reactor**	**Hotel Effluent**	**Hotel irrigation water**
Temperature	°C	Weekly	Weekly	Weekly	Twice	Twice
OD	(mg/L)	Once	Once	Monthly	Once	Once
pH	-	Weekly	Weekly	Weekly	Twice	Twice
Total COD	mg/L	Weekly	Weekly	-	Twice	Twice
Soluble COD	mg/L	Weekly	-	-	-	-
Total BOD5	mg/L	Twice	Twice	-	-	Once
Soluble BOD5	mg/L	Twice	Once	-	-	-
TSS	mg/L	Three times	-	Weekly	Twice	Twice
VSS	mg/L	Three times	-	Weekly	Twice	Twice

Parameters	Sampling Point					
	Unit	Influent	Permeate	Aerated reactor	Hotel Effluent	Hotel irrigation water
Turbidity	NTU	-	Every 15days	-	Twice	Twice
Electrical Conductivity	us/cm	-	Every 15days	-	Twice	Twice
Mg	mg/L	Once	-	-	-	Once
Ca	mg/L	Once	-	-	-	Once
Na	mg/L	Once	-	-	-	Once
Boron	mg/L	-	Once	-	-	Once
Chloride	mg/L	-	Twice	-	-	Once
Chlorine Residual	mg/L	-	Twice	-	-	Once
Bicarbonate	mg/L	-	Once	-	-	Once
NO_3^-	mg N/L	Weekly	Weekly	-	Twice	Twice
NO_2^-	mg N/L	Weekly	Weekly	-	Twice	Twice
NH_4^+	mg N/L	Weekly	Weekly	-	Twice	Twice
TKN	mg N/L	Once	-	-	-	-
TN	mg N/L	Weekly	Weekly	-	Twice	Twice
Soluble TN	mg N/L	Weekly	-	-	-	-
TP	mg P/L	Weekly	Weekly	-	Twice	Twice
Soluble TP	mg P/L	Weekly	-	-	-	-
$PO4^{3-}$	mg P/L	Weekly	Weekly	-	Twice	Twice
TC	CFU/100 Ml	Three times	Three times	-	-	Once
FC	CFU/100 Ml	Three times	Three times	-	-	Once
E.coli	CFU/100 Ml	Three times	Three times	-	-	Once
Sulphide (S)	mg/L	-	Twice	-	-	-
Surfactants	mg/L	-	Once	-	-	-

CHAPTER 4

Results and discussion

The results obtained during this research are reported and analyzed in this chapter, along with the main drawbacks that the system and the MBR operation had.

Firstly, the feed stream of the MBR is characterized. MBR operational conditions, such as membrane permeability and aeration regime are described next. Later, removal efficiencies achieved by the system are studied. Finally, the permeate quality for golf course irrigation and for water body discharges is evaluated.

4.1. Influent characterization

The MBR pilot plant was fed with wastewater coming from the equalization tank. The variation of the main physicochemical features of the influent, relevant to the biological treatment, is shown from Figure 19 to 22.

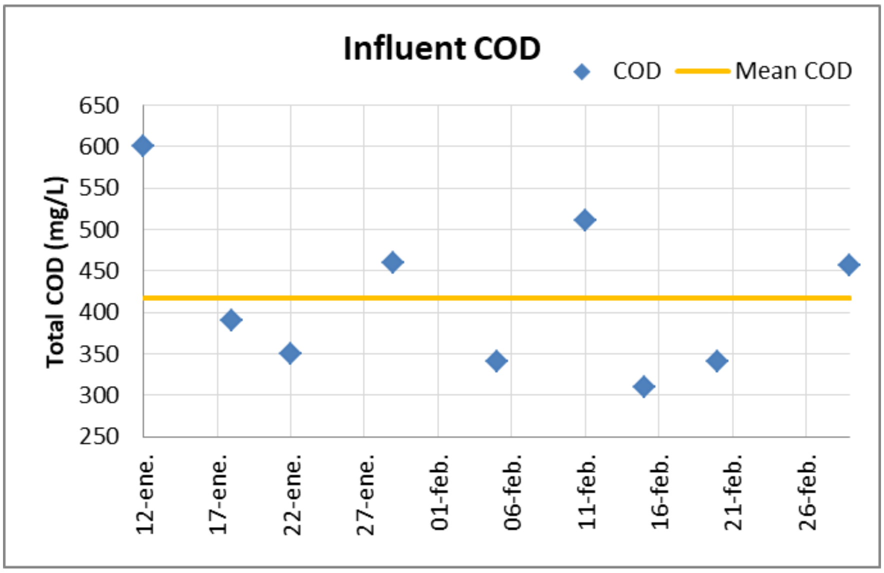

Figure 19 COD concentrations in the influent.

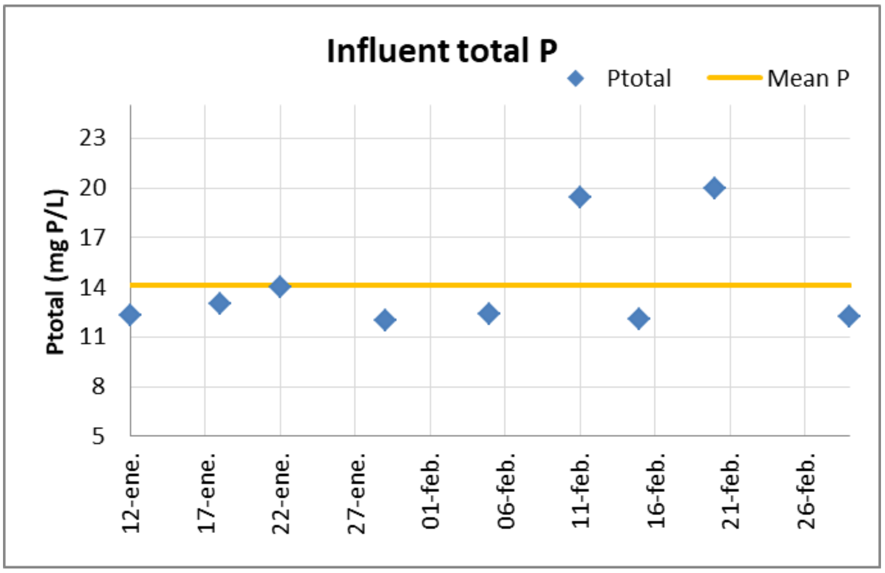

Figure 20 Total P concentrations in the influent.

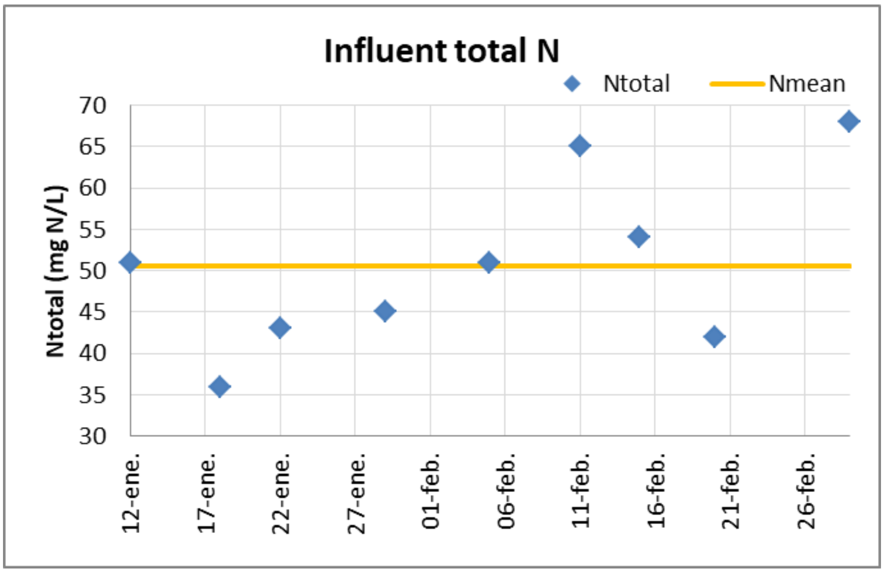

Figure 21 Total N concentrations in the influent.

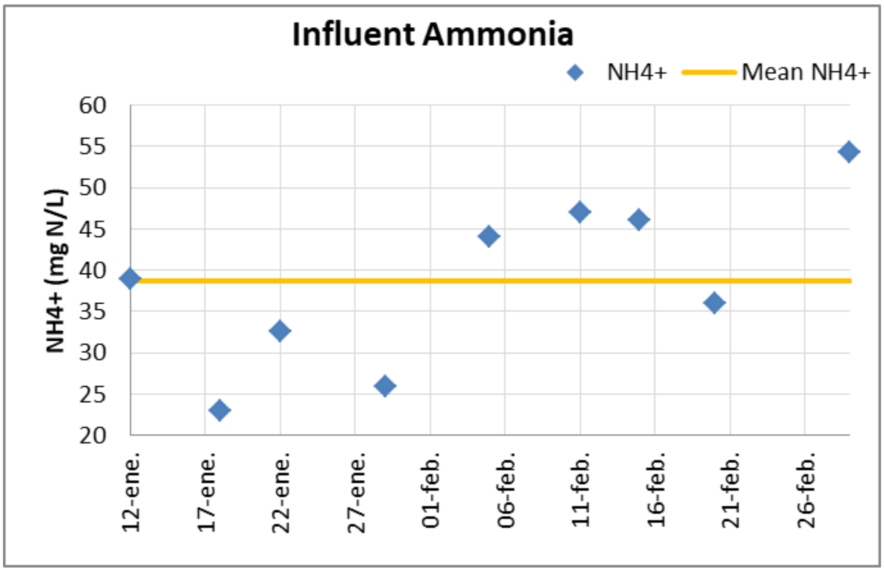

Figure 22 Ammonia concentrations in the influent.

As it can be seen in Figure 19, total COD did not present significant oscillations, except the first value which is 44% higher than the mean value (417 mg/L). This can be explained by the fact that the first days there were a lot of solids in the influent because the sludge level in the septic tank was high and solids were overflowing to the equalization tank. The standard deviation of the data is 96 mg/L, which represents 23% of the average value.

Regarding total phosphorous concentration, it had no major fluctuations and the mean value was 14.2 mg/L, which is the typical concentration for medium loaded raw municipal wastewater (Henze et al. 2008).

When it comes to total nitrogen and ammonia content they present a similar behavior, which is to be expected in domestic wastewaters since ammonia is the main component of the total nitrogen (76% in this case) (Henze et al. 2008).

Table 12 shows the maximum, minimum and mean values obtained for all the influent parameters that were analyzed:

Table 12 Influent characterization.

Parameters	Max	Min	Mean
pH	6.66	6.47	6.56
Temperature (°C)	29.0	25.3	27.6
OD (mg/L)		0.0*	
Total COD (mg/L)	600	310	417
Soluble COD (mg/L)	355	215	262
Total BOD_5 (mg/L)	275-	258	267
Soluble BOD_5 (mg/L)		180*	

Parameters	Max	Min	Mean
Total Ntotal (mg N/L)	68	36	51
Soluble Ntotal (mg N/L)	62	32	45
Total TKN (mg/L)		49.2*	
NO_2^- (mg N/L)	0.18	0.081	0.145
NO_3^- (mg N/L)	0.5	0.3	0.4
NH_4^+ (mg N/L)	54	23	39
PO_4^{3-} (mg P/L)	15.0	10.8	12.7
Total Ptotal (mg P/L)	20	12	14.2
Soluble Ptotal (mg P/L)	14.2	10.2	12.0
SST (mg/L)	58.6	42.7	50.2
SSV (mg/L)	48.0	30.1	38.2
Ca (mg/L)		21*	
Na (mg/L)		48*	
Mg (mg/L)		6.8*	
E.Coli (UFC/100mL)	9.20E05	9.20E05	9.20E05
Fecal Coliforms (UFC/100mL)	9.20E05	9.20E05	9.20E05
Total Coliforms (UFC/100mL)	1.60E06	1.60E06	1.60E06

*Only analyzed once

When evaluating the solids content, TSS and VSS concentrations are low if they are compared to raw municipal wastewater concentrations (between 600 mg and 250 mg TSS/L)-(Henze et al. 2008). What happens is that the influent analyzed came from a septic tank with almost 1 day of hydraulic retention time and a high fraction of the inlet solids had settled in this unit.

The average COD/BOD ratio was 1.6, which means that the influent is readily biodegradable.

The average BOD:N:P ratio was 100:19:5 so, no external addition of nutrients was necessary to achieve biomass growth (100:5:1 is the popularly accepted limit value).

To check if extra nutrients were necessary in the influent for achieving biomass growth, the popular ratio 100:5:1 for BOD: N: P was used. Fortunately, the nitrogen and phosphorous content were high enough to cover the biomass demands and no external addition was needed (100:19:5).

According to the classification of raw wastewater mentioned by Henze et al. (2008), this influent can be classified between low and medium concentrated municipal wastewater.

Regarding the aesthetic quality of the influent, all samples presented the same features: turbid yellow color, low content of suspended solids and a strong ammonia smell (Figure 23).

Figure 23 Influent sample

4.2. MBR operational conditions

Operational conditions of the reactor are summarized in Table 13 and developed in the following sections.

Table 13 MBR operational conditions.

Average flow rate (m3 d^{-1})	1.87
Sludge retention time (SRT, days)	Infinite
Average hydraulic retention time (HRT, hrs)	15.9
Filtration time (min)	10
Backwash time (min)	1
Average permeate flux (L/m^2.h)	11.9
Average permeability (L/m2.h.bar)	73.9

4.2.1. Flux and permeability

Permeate daily flow and average flow rate of the whole period are shown in Figure 24.

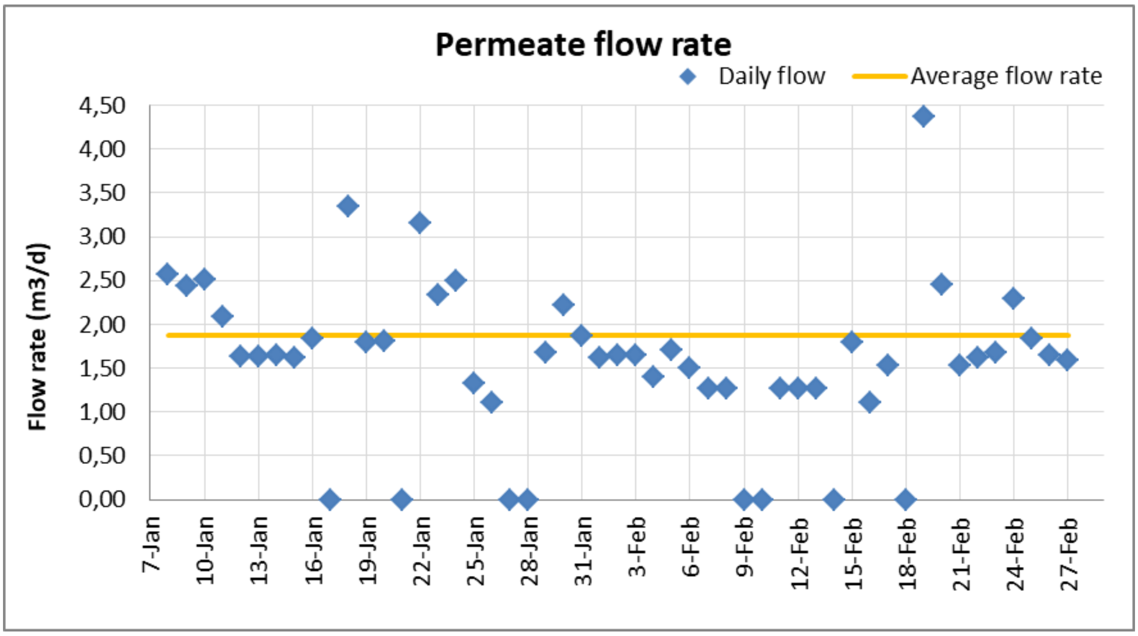

Figure 24 Permeate flow rate variations along the research period.

It can be observed that there were 8 days when the flow rate was zero. In most of those cases, the system was out of operation due to blackouts, automatic computer restarts or PLC failures where it wrongly registered that the maximum acceptable pressure was reached.

However, the 27th and 28th of January the flow rate was zero not because the system was turned off, but because the permeate pressure slowly started to increase until it turned slightly positive (Figure 24).

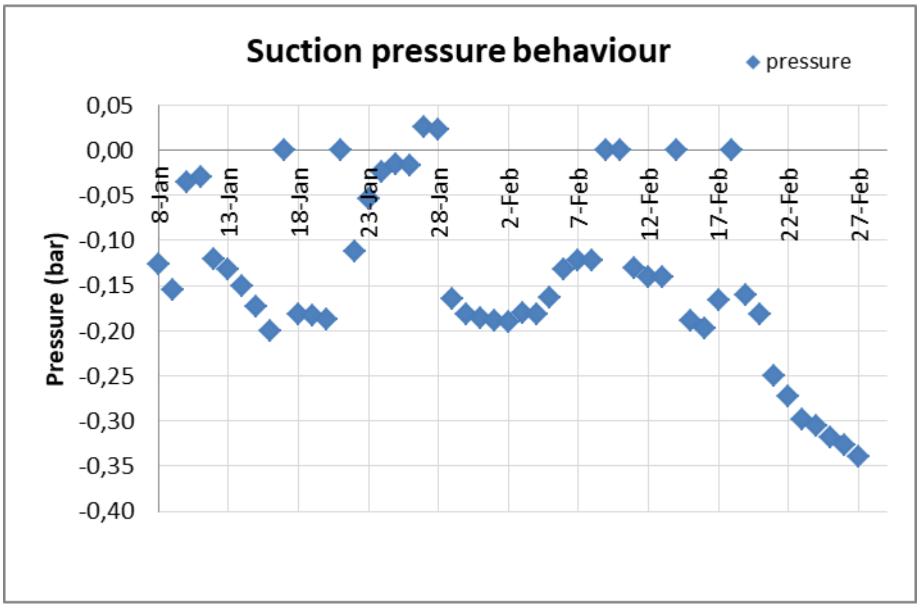

Figure 25 Suction pressure variations over the research period.

This episode that goes against the typical operation can be explained by a failure of the reversible pump. Due to the equipment vibrations, the joint between the permeate pipeline and the reversible pump was loosed and the input of air did not allow the system to increase the suction pressure. The 29th of January, the permeate valve was open until reaching the usual working pressure (-0.16 bar) and from that situation, the system worked without any inconvenience. The next visit (5th February) the suction and backwash pressures were okay but a leak was observed in the reversible pump (Figure 26). What happened is that when the permeate valve was adjusted the 29th of January, the permeate flowrate increased, displaced the air input coming from the loose joint and the permeate started to leak from it.

Figure 26 Leaking reversible pump

The suction pressure was also very low the first days of operation (10th and 11th of January), but the flow rate did not change significantly. In this case, the suction pressure decrease was due to the presence of small obstructions in the pipelines that were removed once the system started its continuous operation.

Figure 27 shows an example of the normal filtration cycles, where the vacuum pressure increases until the backwash is implemented and the suction pump inverts its flow direction for a minute (pressure turns positive).

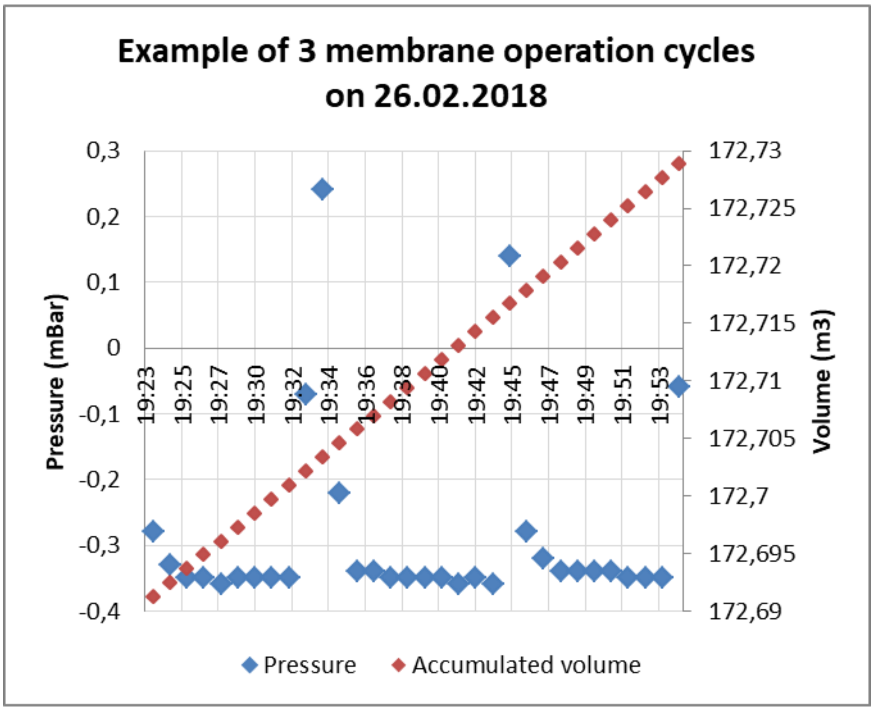

Figure 27 Example of 3 cycles of the membrane operation.

To summarize, Table 14 reports the maximum, minimum and average pressures achieved during backwash and filtration operations:

Table 14 Pressure measurements during the research period.

Absolute Pressures	Average (bar)	Max (bar)	Min (bar)
Backwash	0.177	0.400	0.070
Suction	0.172	0.380	0.010

It should be highlighted that the maximum pressure acceptable by the system was never reached during this two months of operation and no costs in chemical products for membrane cleaning was necessary.

Regarding the system permeability, the average value was 73.9 L/h.m^2.bar. For this calculation, days 10th,11th, 24th, 25th and 26th of January were not included because those days were not representative of the usual operation of the reactor.

The average permeability obtained during the MBR operation was around 40 % higher than the permeability values achieved in the previous projects that used the same pilot MBR. This was expected, since they worked with higher MLVSS and influent concentrations (Cunha 2015; Fraga et al. 2017). Plus, they may have worked with a different air flowrate for membranes scouring.

As higher permeabilities can be achieved when using other membrane configurations and suppliers (Table 15); its selection is a key factor to considered for the design of a MBR plant.

Table 15 Permeability values reported for municipal wastewater pilot plants (Judd 2006).

Kubota (Flat sheet)		Mitsubishi Rayon (Hollow Fiber)		Zenon (Hollow Fiber)	
L/m^2h	L/m^2h bar	L/m^2h	L/m^2h bar	L/m^2h	L/m^2h bar
8.3-12.5	500	5-8	200	20	225
32.5-42	350	20	145	35	225
25	250	20-25	140	37,2	270
26	650	16-24	66	6.2-29.6	124
18-25	200-500	4.8	90	16-31	61-120
15-16	300			10	200
9.5	200				

Daily variations of the operation permeability of the membranes are illustrated in Figure 28

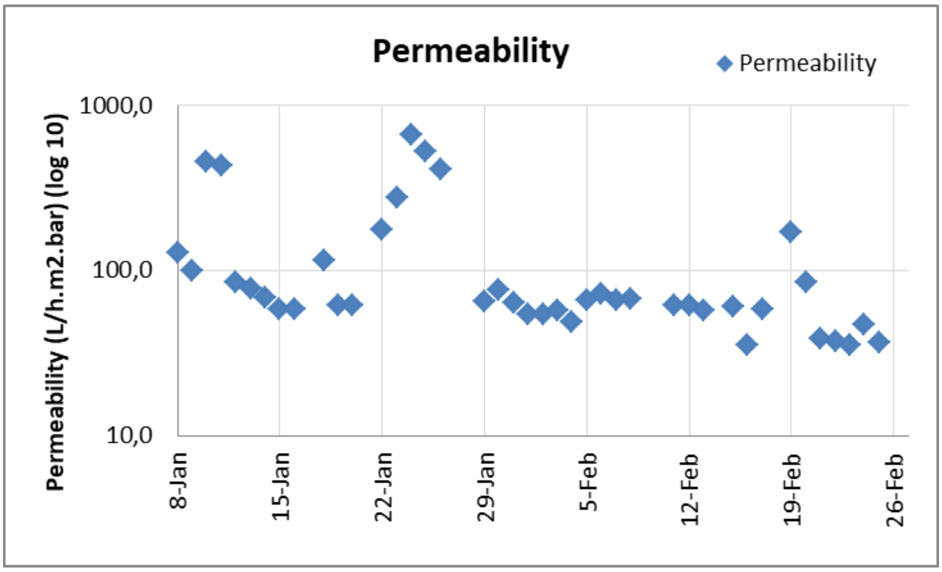

Figure 28 Membrane permeability during the research period.

To sum up, the reactor worked without major inconveniences and according to the expectations. Due to the low load of solids in the influent and in the reactor, plus the benefit of operating new membranes, it was possible to achieve higher permeabilities and flowrates than previous projects, without compromising the membrane units or the effluent quality.

4.2.2. Physicochemical parameters of the aerated compartment

Dissolved Oxygen (DO)

The air blower worked full time in order to supply continuous air membrane scouring. Plus, the operation of the fine bubble diffuser was maximized to ensure enough DO for nitrification. Under these conditions, the DO value achieved in the reactor was between 3.01

and 3.83 mg/L, which is an acceptable range. According to Henze et al. 2008, the lower limit of DO concentration that is usually adopted for designing nitrification systems is 2 mg/L. Regarding the upper limit, OD concentrations up to 33 mg/L do not affect nitrification.

pH

The pH of the mixed liquor was, on average, 6.54. However, the 29th of January the pH decreased to 5.09, as a consequence of the improper operation of the reactor. During those days, the suction pressure was almost inverted and the hydraulic retention time of the liquid increased. As there was no water renewal and nitrification was occurring, pH went down. To reverse this situation as soon as possible, these three measures were taken:

- Permeate valve was wide open to remove the acid liquid fast
- The influent pump was turned on to dilute the acid liquid
- Around 200 grams of sodium bicarbonate were added to the anoxic chamber and the recirculation pump was turned on so to homogenize the liquid inside the anoxic and aerobic compartment and quickly increase the pH up to 8.5.

According to Henze et al. 2008, for a pH range between 5.5 and 7.2, nitrification activity drops exponentially with the pH and at a pH of 5, the nitrifying specific growth rate decreases more than 85% when comparing it to the values obtained at a pH range of 7.2 and 8.

During the MBR operation, the pH in the reactor was neither a significant inhibitory factor nor an optimum one (between 7 and 8 would have been the best condition).

Temperature

The main temperature of the mixed liquor was 26.5 °C, which is within the optimum range for nitrifying bacteria development.

4.2.3. MLTSS and MLVSS

As the concentration of solids in the reactor was always lower than the designed one, the reactor was operated without sludge waste (infinite SRT).

Figure 29 shows the variation of the solids concentration inside de MBR aerated compartment:

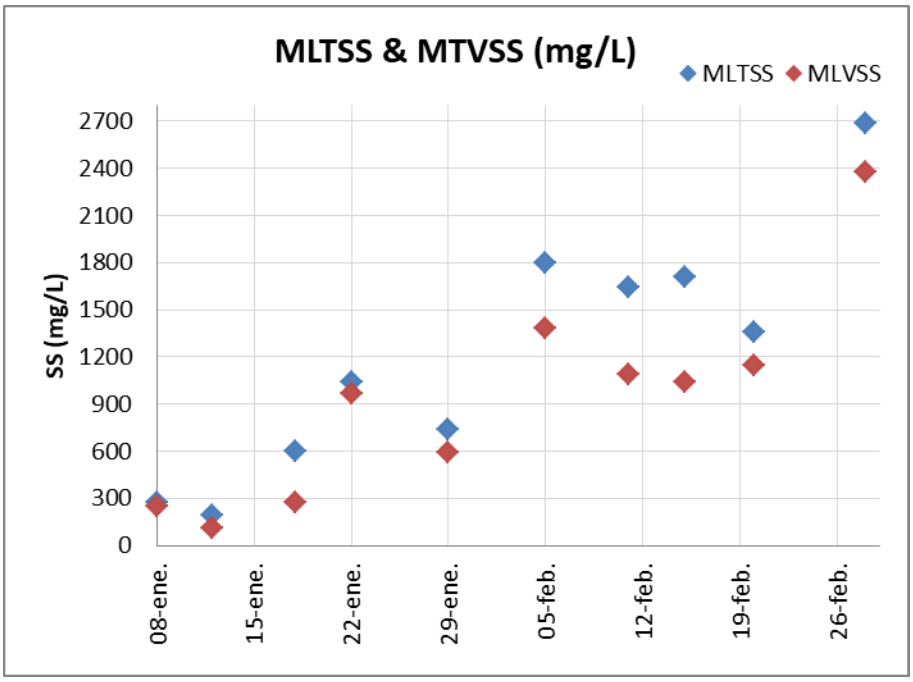

Figure 29 MTSS and MVSS concentrations in the aerated compartment of the MBR.

The final concentration of VSS achieved in the reactor (2400 mg/L) is lower than the concentration expected. According to the calculations presented in Appendix C, that concentration should have been reached within 15 days of operation. Nevertheless, taking into account the ups and downs of the reactor operation and the pH incident, the biomass growth obtained is coherent.

Regarding the final TSS concentration (2685 mg TSS/L), it was 75% lower than the design one (10000 mg/L). However, the final value reached was comparable to the operational conditions of a traditional CAS system (Henze et al. 2008) and biological removal of organic matter was not affected.

A picture of the mixed liquor (mixed and floated) the last day of operation is shown below (**Figure 30**):

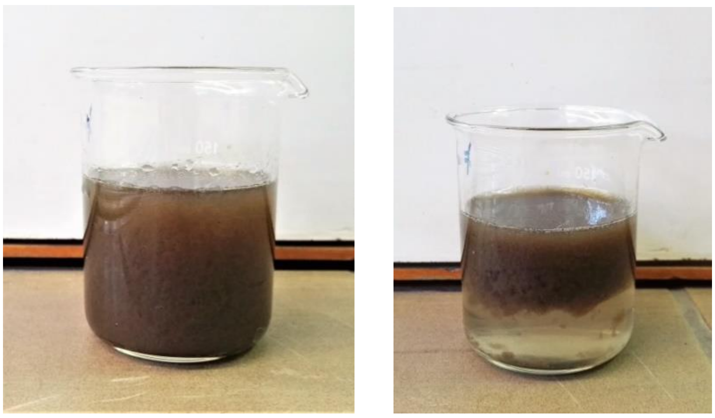

Figure 30 Mixed Liquor last day of operation (mixed and floated).

4.3. Evaluation of the MBR performance

4.3.1. Organic matter

Permeate COD and influent total and soluble COD concentrations can be compared in Figure 31:

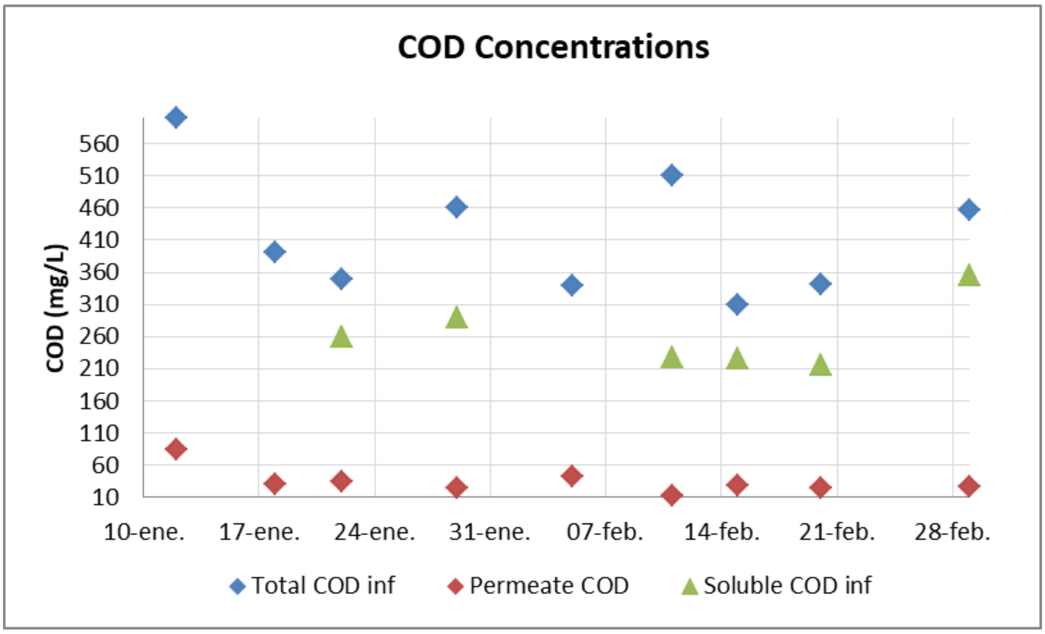

Figure 31 COD concentration in the influent and permeate over the research period.

The maximum, minimum and mean total COD removal efficiencies were 98%, 86% and 93% respectively, which meets the values reported in literature ((Merz et al. 2007; Paris and Schlapp 2010; Verrecht et al. 2012; Santasmasas et al. 2013; Atanasova et al. 2017).

If we compare these numbers with the current removal efficiency of the hotel CAS system, it is between 34 and 40% higher. The main reason for this difference is that the secondary settler of the hotel cannot deal with the hydraulic load during high season and the sludge particles escape with the effluent. This problem is a key factor in many CAS wastewater treatment plants that in order to prevent this issue have to design large secondary settlers, which significantly increase the footprint of the treatment plant.

If soluble COD in the hotel effluent is considered (in average 51.4 mg/L), the efficiency of the MBR system is only 5% higher than the CAS system.

To check that the organic matter was not only being removed by the ultrafiltration membranes but also because of the biological activity in the reactor, influent soluble COD was analyzed and compared with the permeate COD. In this case, the mean removal efficiency was 90%, almost the same as the total COD removal efficiency. This reflects that most of the COD load was soluble and that microorganisms were working properly.

Regarding the BOD_5 concentrations, due to time and costs issues, it was only analyzed 2 times during the research period. The average removal efficiency achieved was 94%. Table 16 shows the BOD_5 concentrations in the influent and permeate:

Table 16 BOD5 concentrations in the effluent and permeate.

	Influent (29.01.2018)	Permeate (5.02.2018)	Influent (12.02.2018)	Permeate (19.02.2018)
BOD_5 (mg/L)	258	26	275	7.5

4.3.2. Nutrients

Taking into account that one of the aims of this research was to study the quality of the permeate for irrigation and its input of nutrients, their removal was not desired. Only nitrification was promoted during the MBR operation so to calculate the ammonia removal efficiencies of the system and to verify if the ammonia concentration values in the permeate comply with the national standards for waterbody discharge.

Nitrification

Figure 32 illustrates the concentration of ammonia in the influent and in the permeate, and the concentration of nitrate in the permeate:

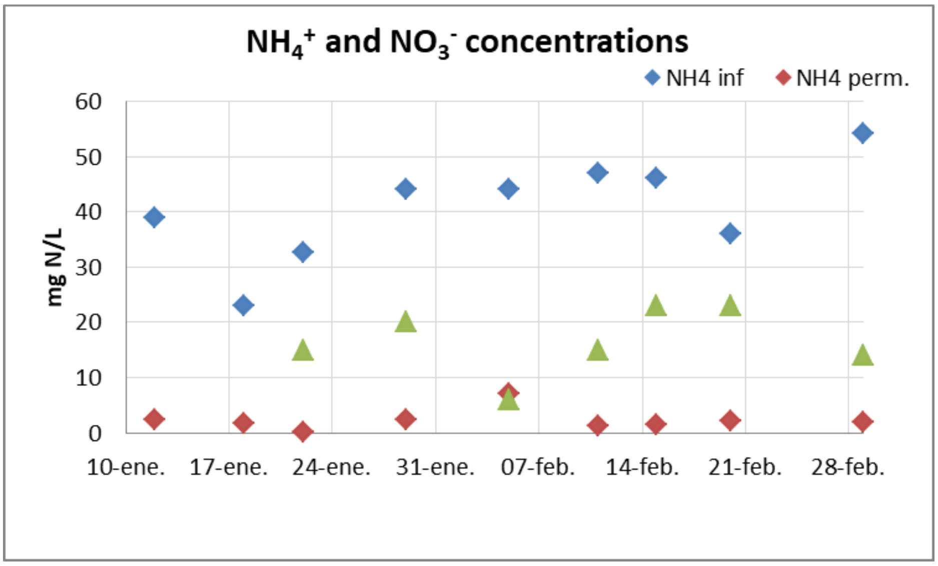

Figure 32 Ammonia concentration in the influent and permeate over the research period.

The maximum, minimum and mean ammonia removal efficiencies were 99%,84% and 94%.

Total nitrogen

The total nitrogen takes into account the ammonia, nitrate, nitrite and organic nitrogen concentrations. When the influent is biologically treated and nitrification and denitrification take place, the total nitrogen in the effluent is lower than the one in the influent due to nitrogen uptake for biomass growth (0.10 gr N/gr VSS) and due to N_2 (g) production by denitrifies (Henze et al. 2008).

Table 17 summarizes the total nitrogen concentrations in the influent and permeate:

Table 17 Total nitrogen concentrations in the influent and permeate.

Date	TNinf (mg/L)	TNeff (mg/L)	TNtinf-TNteff
12-ene	51	32	19
18-ene	36	16	20
22-ene	43	16	27
29-ene	45	29	16
05-feb	51	24	27
11-feb	65	22	43
15-feb	54	32	22
20-feb	42	34	8
01-mar	68	20	48

There were days where the difference between the nitrogen concentration in the permeate and the influent was significantly high to be related only to nitrogen biomass uptake (>20 mg/L). One possible explanation is that even though the recirculation rate was minimized, partial denitrification occurred in the first compartment, where dissolved oxygen concentrations were lower. Another explanation is the possible growth of aerobic denitrifiers: according to Ji et al. (2015), these microorganisms work efficiently at warm temperatures, neutral pH, DO concentrations between 3-5 mg/L and at C/N load ratios between 5 and 10 mg/L). All these features, but the pH (which was around 6.5), were met in the MBR operational conditions.

The permeate nitrogen composition was also evaluated (Table 18).

Table 18 Nitrogen composition in the permeate.

Date	N total (mg N/L)	NO_2^- (mg N/L)	NO_3^- (mg N/L)	NH_4^+ (mg N/L)	NH4+NO2+NO3 (mg N/L)	N org calculated (mg N/L)
22-ene	16	<1	15	0.21	15.2	0.8
29-ene	29	0,23	20	2.4	22.6	6.4
11-feb	22	0,34	15	1.3	16.6	5.4
15-feb	32	1,59	23	1.5	26.1	5.9

Date	N total (mg N/L)	NO_2^- (mg N/L)	NO_3^- (mg N/L)	NH_4^+ (mg N/L)	NH4+NO2+NO3 (mg N/L)	N org calculated (mg N/L)
20-feb	34	1.17	23	2.1	26.3	7.7
01-mar	20	0.53	14	2	16.53	3.5

When calculating the organic nitrogen in the effluent (as the difference between total nitrogen and the sum of ammonia, nitrite and nitrate) its concentration was higher than expected. According to literature data (Henze et al. 2008; Czerwionka et al. 2012), in secondary treated municipal wastewater the soluble organic nitrogen concentration is not higher than 2 mg/L, due to the transformation of organic biodegradable nitrogen into free and saline ammonia.

If the unbiodegradable soluble organic nitrogen (USON) is calculated considering a fraction of 0.03 of the average TKN in the influent (used by Henze et al. 2008), the USON concentration in the permeate would be 1.5 mg/L.

The difference between the values obtained in the laboratory and the ones calculated was due to the analytical methods. The total nitrogen technique has an accuracy of ± 5 mg/L and the ammonia and nitrate determination an accuracy of ±1.6 and ± 1.2 mg/L respectively. If these ranges of error are considered, total nitrogen concentrations obtained in the permeate could have been 5 mg/L lower and the permeate organic nitrogen values calculated would go from 0 to 2.7 mg/L.

Phosphorous

To check the phosphorous uptake by the microorganisms, the phosphate concentration in the influent and permeate were compared (Figure 33).

The removal efficiencies went from 0% up.to 20%. These values were compared with the COD removal obtained the same days to check if the variation in phosphorus uptake was because of the variation of the organic load in the reactor. However, no clear correlation was observed. Results can be found in Table 19.

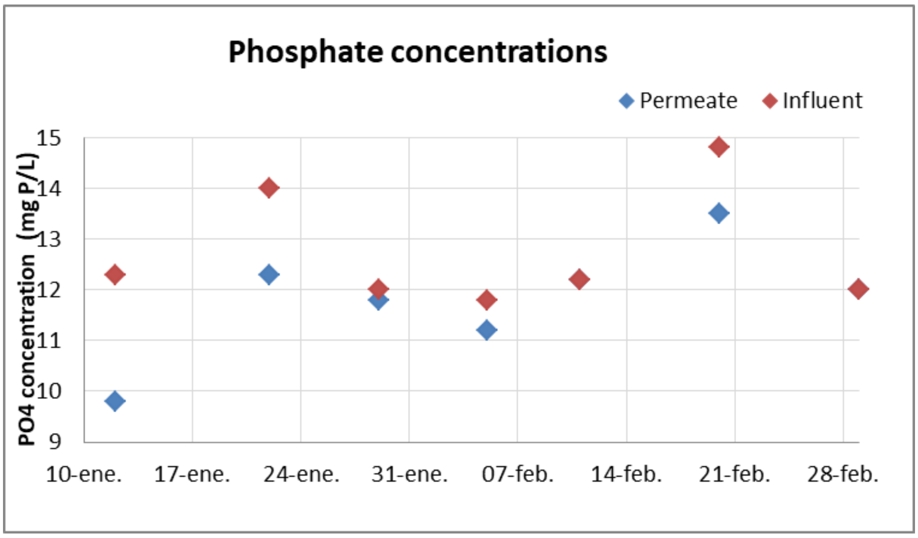

Figure 33 Phosphate concentrations.

Table 19 Phosphate and COD analysis.

	PO43- (mg P/L)		Removal efficiency	PO43- removal (mg/L)	COD removal (mg/L)	PO4/COD
	Influent	Permeate				
22-ene	14	12.3	12%	1.7	225.0	7.56E-03
29-ene	12	11.8	2%	0.2	265.0	7.55E-04
05-feb	11.8	11.2	5%	0.6	298.0	2.01E-03
11-feb	12.2	12.2	0%*	0	216.4	-
20-feb	14.8	13.5	9%	1.3	189.9	6.85E-03
01-mar	12	12	0%*	0	328.8	-

*The accuracy of the laboratory technique is ±0.4 mg/L.

Regarding the total phosphorous removal efficiencies, the maximum, minimum and average values obtained were 37%, 2% and 15% respectively. These values are lower than the concentrations mentioned in literature, where efficiencies between 30 and 60% were reported (Libralato et al. 2009; Cunha 2015). According to Ghehi et al. (2014); Arón (2015); phosphorous removal efficiencies can change significantly depending on the C:N:P ratio and efficiencies up to 90% can be reached if phosphorous removal is properly promoted in the reactor.

4.3.3. Pathogens

The removal efficiencies achieved by the system regarding E.Coli, fecal coliforms and total coliforms are shown in Table 20. These results were expected according to the literature data (Atanasova et al. 2017).

Table 20 Pathogen removal efficiencies achieved.

Parameter	Average influent concentration	Average permeate concentration	Log 10 removal
E.Coli (UFC/100mL)	9.20E+05	4.83E+01	3 to 4
Fecal Coliforms (UFC/100mL)	9.20E+05	5.43E+01	3 to 4
Total Coliforms (UFC/100mL)	1.26E+06	1.05E+03	3 to 4

4.4. Water quality evaluation

4.4.1. Permeate quality for golf course irrigation

In this section, the permeate features are evaluated considering its potential for golf course irrigation. First, the permeate quality is compared to the international standards to check if it is a safe water source for the hotel population. Then, the permeate is evaluated according to the national irrigation law. A summary of recommended values for the main agronomic parameters are presented later. Finally, the actual irrigation water of the hotel is compared to the permeate and its use as a golf course fertilizer is evaluated.

Permeate reuse and international standards for water reclamation

Firstly, the permeate quality is compared to EPA standards (2012) for water reclamation in restricted and unrestricted urban areas (Table 21):

Table 21 Comparison between permeate quality and EPA water reuse standards.

Parameter	Permeate			EPA limits for Urban areas	
	Max	Min	Mean	Restricted	Unrestricted
pH	7.37	5.90	6.64	6-9	6-9
BOD_5 (mg/L)	26	7.5	17	≤10	≤30
Turbidity (NTU)	2.1	0.8	1.5	≤2	-
TSS(mg/L)	-	-	-	-	≤30
Faecal Coliform (UFC/100mL)	110	33	71,5	Not detectable	≤200
Cl_2 residual (mg/L)	<1.6E-5	<1.6E-5	<1.6E-5	1	1

It can be seen that Fecal Coliforms, turbidity and BOD_5 parameters can be higher than the recommended values for water irrigation in unrestricted areas. That means that following EPA recommendations, the hotel should fence the area that would be irrigated with the permeate or should put warning signs to prevent the guests being in touch with that water.

On the other hand, if WHO (2006) and UNEP (2005) guidelines are considered, the permeate quality meets the standards and there is no health threat in its use for irrigation.

Other relevant features to increase the population acceptance of wastewater reuse are its color and odor. During this research, the permeate achieved excellent conditions (Figure 34):

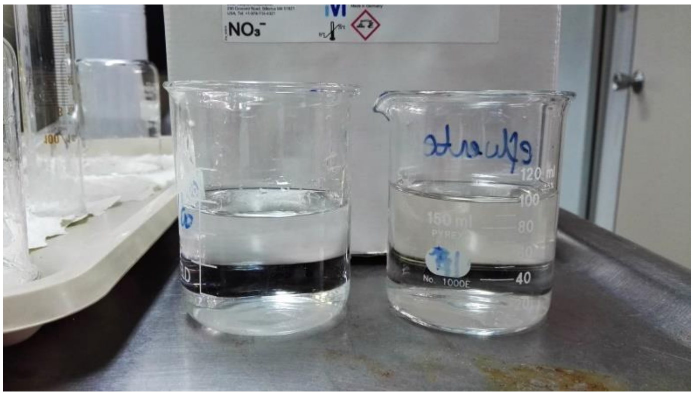

Figure 34 Visual comparison between tap water (left) and the MBR permeate (right).

Permeate quality and Uruguay's national irrigation guidelines

According to Uruguay's water classification for field irrigation (Table 9), the permeate quality would be class 1 and it would be possible to use it unrestrictedly since it would have no severe impacts on the soil (Table 22):

Table 22 Comparison between permeate quality and Uruguay standards (2003) for irrigation.

	Permeate			Uruguay irrigation guideline
	Max	**Min**	**Mean**	**Class 1 standards**
EC (mS/cm)	0.693	0.611	0.652	<2
pH	7.37	5.90	6.64	-
SAR(meq/L)		2.7*		<6
Bicarbonate (mg $CaCO_3$/L)		52.8*		<250
Chloride (mg/L)	51.9	41.9	46.9	<150

*Only analyzed once

It should be highlighted that this classification is focused only in soil preservation and does not contemplate treated wastewater irrigation and its potential health risks.

Since there are no national guidelines for water reclamation, DINAMA has the right to establish, for each project in particular, the control parameters and the water standards to accomplish.

The SAR and Na values presented for the permeate in Tables 22, 23 and 24, are actually the ones calculated for the influent. Considering that metal ions are not retained by ultrafiltration membranes(Garcia 2017) and that the metal uptake for biomass growth is negligible, the concentration of Na, Ca and Mg should not change significantly between the permeate and the influent.

Permeate quality and main agronomic features

Table 23 summarizes the agronomic permeate parameters and compares them with the recommended values for turfgrass, according to Landschoot:

Table 23 Comparison between permeate quality and recommended agronomic values.

Parameters	Permeate			Recommended value (Landschoot)
	Max	Min	Average	
pH	7.37	5.90	6.64	6-7
Bicarbonate (mg $CaCO_3$/L)		52.8*		<120
EC (Ds/m)	0.693	0.611	0.652	0.31-0.78
Na (mg/L)		37*		<70
SAR		2.7*		<3
Chloride (mg/L)	51.9	41.9	46.9	<100
Boron (mg/L)		<0.050*		<2

*Only analyzed once

Taking into account FAO guidelines (Table 7), the permeate could slightly affect the water infiltration rate because it has a SAR lower than 3 and an EC between 0.7 and 0.2 Ds/m.

On the other hand, if turf grass recommendations are considered, the permeate complies with all the parameters and has acceptable attributes for golf course irrigation. The main parameters to monitor are Ca, Mg and Na, to ensure that their ratio would not change and that the SAR would still be below the limit.

Permeate quality versus hotel irrigation water

Nowadays, the hotel irrigates its green areas with water from a large pond located within the hotel property This pond receives rainwater and the runoffs of the surroundings (Figure 35).

Figure 35 Irrigation water pond.

The following table (Table 24) compares the average values of the permeate with the hotel irrigation water:

Table 24 Comparison between permeate and river mean values.

Parameters	Mean values	
	River	Permeate
pH	7.72	6.64
Temperature (°C)	25.2	27.8
Total COD (mg/L)	31	28
Total Ntotal (mg N/L)	1.0	25
$PO4^{3-}$ (mg PO4-P/L)	1.8	11.9
TSS(mg/L)	25.6	-
VSS (mg/L)	2.4	-
Turbidity (FAU)	29.5	3.2
Turbidity (NTU)	4.9	1.5
DO (mg/L)	6.48	4.49
E.C. (dS/m)	0.419	0.652
SAR	2.3*	2.7*
Na (mg/L)	48	37
Bicarbonate (mg CaCO3/L)	154*	52.8*
Chloride (mg/L)	20.7	46.9
Boron (mg/L)	<0.15*	<0.050*
Total Coliforms (UFC/100mL)	3.50E+05	920
Fecal Coliforms (UFC/100mL)	<1800	71.5
E.Coli (UFC/100mL)	<1800	63.5

*Only analyzed once

The main drawbacks of the pond water are its lack of nutrients for soil fertilizing and the pathogens content that can be a potential health risk for the guests.

When comparing the organic matter concentrations, both streams have similar concentrations.

Regarding the aesthetic features, the permeate always presented turbidities lower than 4 FAU. On the other hand, in one of the samples, the hotel irrigation water reached 53 FAU, presenting a slightly brownish color (Figure 36).

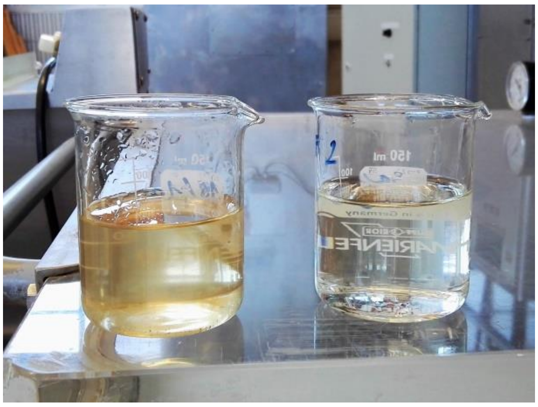

Figure 36 Hotel irrigation water (left) and permeate (right).

To sum up, the permeate does not present severe health or agronomic risks for being reused for golf course irrigation. Moreover, regarding pathogens, suspended solids, turbidity, and nutrients, the permeate has better conditions than the actual irrigation water.

The next question to be addressed is whether the permeate flow rate and nutrient concentrations are high enough to cover the golf course water and macronutrients demands.

Regarding the water consumption for irrigation, the hotel consumes 15.000 m^3/month, which is almost 28 times the average effluent generation per month. This means that the permeate could be completely used for irrigation but the water savings in irrigation are negligible.

When it comes to golf course fertilization, only the greens are improved with an external input of nutrients.

The hotel has 15 greens of 500 m^2 each that are fertilized with ammonium sulfate and potassium chloride every fifteen days. The annual demand for nitrogen and potassium for all the greens is 180 kg of each. Taking a 5:1 ratio between nitrogen and phosphorous (Busso 2012), the annual phosphorous requirement for all the greens would be 36 kg.

Considering the average effluent flow rate of the hotel (17.7 m^3d^{-1}) and the mean phosphate and nitrogen concentrations obtained in the permeate, the average input of nutrients into the soil could be 77 kg of phosphorous and 126 kg of nitrogen per year. These results show that the overall nutrient demand for the greens could not be totally covered with the permeate flow. Nevertheless, as the nutrients distribution over the year changes according to the season, there could be months where the permeate nutrients could be enough for fertilization.

Based on the information reported by Busso (2012), monthly requirements of nitrogen were calculated and compared with the nitrogen input of the permeate (Table 25). For this calculation, it was considered that the hotel is at its full capacity from December to February and that the permeate concentrations do not change over the year. The nitrogen concentration considered in the permeate was the average values of nitrate and ammonia together:

Table 25 Monthly distribution of nitrogen dosage over the year.

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Total N demand (kg/month)	9.0	11.3	15.8	20.3	20.3	13.5	11.3	13.5	18.0	18.0	18.0	11.3	**180**
Permeate N load (kg/month)	19.2	19.2	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	19.2	**126**

According to the calculations, the nitrogen concentration in the permeate would be enough to cover the greens' nitrogen demand only in summer. The rest of the year, the nitrogen deficit in the permeate goes from 32% to 62%, depending on the month. The total amount of ammonium sulfate that could be saved in a year is 478 kg (100Kg of nitrogen).

Phosphorous fertilization over the year was also estimated. Table 26 shows the results:

Table 26 Monthly distribution of phosphorous dosage over the year.

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Total P demand (kg/month)	1.8	2.3	3.2	4.1	4.1	2.7	2.3	2.7	3.6	3.6	3.6	2.3	**36.0**
Permeate P load (kg/month)	11.8	11.0	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	11.8	**77.5**

In this case, greens' phosphorous demand could be covered by the permeate load, and the savings would be 78,3 kg of triple superphosphate per year.

When using the permeate as a fertilizer, a fact to consider is that the ratio between nitrogen and phosphorous (5:1) is not accomplished. The main constraint of overdosing phosphorous is its potential for increasing eutrophication when reaching surface waterbodies due to runoffs or contaminated groundwater streams (King et al. 2001). To prevent this, phosphorous removal should be enhanced in the MBR unit.

Another key factor to take into account is the frequency of fertilization. Nowadays, macronutrients are applied every fifteen days. If permeate irrigation is to be considered, the irrigation should be done every day to minimize the size of the storage tanks. Plus, if permeate water is stored for 15 days; further disinfection is required to prevent biomass growth in the storage units.

It should be mentioned that the excess of nitrogen in the permeate during high season is not a problem because it can be irrigated in other areas of the golf course (tees or fairways). Nowadays, the hotel has limited the fertilization to the greens only for economic reasons.

4.4.2. Permeate discharge into water bodies

Considering the hotel location (next to Colonia bay), permeate quality was also compared with the Uruguayan standards for water bodies discharge (Table 27):

Table 27 Comparison between permeate quality and Uruguayan regulations for water body discharges.

	Permeate			Uruguay Decree 253/79
	Max	**Min**	**Mean**	**Water course discharge**
Temperature (°C)	28.9	26.6	27.8	<30
pH	7.37	5.90	6.64	6-9
TSS (mg/L)	0	0	0	150
BOD5	26	7.1	16.7	60 (mg/L)
Anionic Surfactant (mg/L)		1.1E-4*		4
Total Phosphorous (mg P/L)	13.5	9.8	12.1	5
Total Kjeldahl Nitrogen (mg N/L)		No data		10
Ammonia (mg N/L)	7,1	0,21	2,29	5
Nitrate (mg N/L)	23	6	17	20
Sulfide (mg/L)	<0.1	<0.1	<0.1	1
Thermoresistant Coliforms (UFC/100mL)	110	33	71.5	5000

***Only analyzed once.**

All average values are below the decree limit, but total phosphorous.If the permeate is to be discharged in rivers, phosphorous removal should be enhanced. To be on the safe side, denitrification should also be promoted on the MBR operation.

Regarding TKN, even though there is no value, its concentration should accomplish the standards because ammmonia concentration is low and, as it was discussed before, organic nitrogen should also be very low in the permeate (<2 mg/L).

4.4.3. Comparison between permeate quality and hotel effluent quality

The following table (Table 28) compares the most important parameters of the permeate with the ones of the hotel effluent:

Table 28 Comparison between permeate and hotel effluent quality.

Parameters	Mean values	
	Hotel Effluent	Permeate
pH	7.24	6.64
Temperature (°C)	27.4	27.8
Total COD (mg/L)	168	28
Soluble COD (mg/L)	52	-
Total Ntotal (mg N/L)	40.4	25.0
Soluble Ntotal (mg N/L)	30.0	-
NO2- (mg N/L)	0.129	0.772
NO3- (mg N/L)	<5	17
NH4+ (mg -N/L)	30.8	1.9
PO43- (mg P/L)	12.4	12.0
Total Ptotal (mg P/L)	22.2	12.1
Soluble Ptotal (mg PO4-P/L)	11.2	-
TSS(mg/L)	59.2	-
VSS (mg/L)	41.6	-
Turbidity (FAU)	85.5	3.2
DO (mg/L)	0.0	4.49
E.C. (dS/m)	0.879	0.652
F.C. (UFC/100Ml)	28000	71

As it was mentioned before, the bottleneck of the hotel CAS treatment plant is the secondary settler and it can be noted because there is a striking difference (69%) between soluble and total COD in the effluent. Moreover, this operative constrain also affects the final effluent quality regarding fecal coliforms, solids and turbidity.

When comparing the ammonia and nitrate effluent concentrations with the ones of the permeate, it can be seen that there is no nitrification process taking place in the aerated reactor of the hotel. This can be improved by increasing the air supply and by controlling the sludge retention time, which nowadays is not being quantified.

4.5. Main drawbacks of the MBR pilot system and operation

The main drawbacks and MBR practical details observed during the operation of the pilot plant are summarized in Table 29:

Table 29 Main drawbacks detected during the operation of the pilot-scale MBR.

Drawback	Comments and suggestions
Permeate and overflow pipelines are connected	This is an important fact to consider when locating the pilot plant since it should be next to a discharge point/system unit capable of receiving raw wastewater.
There is no valve for emptying the reactor	All the compartments of the unit but the permeate tank have no emergency valve for emptying the unit, which makes this operation more demanding and time-consuming.
There is no sludge pump nor valve for emptying the sludge compartment	This is something to take into account for further projects: the places of research should have its own sludge pump and a sludge treatment unit. Plus, the MBR should be installed near them.
Influent pump capacity is too much for the treatment capacity of the unit	The influent pump flow is 1 m^3/hr, while the reactor was designed for treating a daily flow of 1 m^3. In order to achieve a better continuous operation, a bypass could be installed in the inlet pipeline so to have another element for controlling the inlet flow (is difficult to accurately regulate the existing inlet valve).
Air blower capacity can be too high and oxygen supply can be difficult to control	An air purge could be installed in the air pipeline in order to have a better control over the air supply without compromising the reactor operation or the air blower engine.
Unequal distribution of air among the membranes	A recommendation for further projects: when locating the MBR check the inclination of the floor and avoid bumpy surfaces. Although the height of the membranes can be regulated, if the liquid surface is not horizontal, it is very difficult to achieve equal air distribution for the membranes.
Lack of continuous dissolved oxygen meter	Considering that the air supply regime can be controlled with the PLC software, the pilot plant could be improved by installing an online DO meter, so it can be continuously monitored and operation parameters could be adapted to the reactor conditions immediately..

Regarding the operation of the MBR during this project, the main drawback was that the hotel was located in Colonia and it was not possible to monitor the reactor in person every day. Moreover, as the hotel was at its full capacity, there was not enough manpower available for taking care of the pilot treatment plant and helping with its operation.

Another drawback was that the installation of the equipment took more time than expected and the MBR was only operative for two months and could not reach the steady state.

Finally, the fact that LATU laboratories take so much time for doing any analysis limited the sampling methodology and, key parameters such as TKN, Na, Mg and Ca were not delivered on time. For next projects, it is highly recommended to work with an external laboratory.

CHAPTER 5

Economic evaluation

5.1. Introduction

Taking into account the promising results reported in the previous chapter, an economic evaluation was carried out to determine the costs and economic benefits of implementing the MBR technology in this hotel.

5.2. Assumptions and considerations

The following considerations were taken into account for making the economic evaluation:

- It was designed a full-scale MBR plant (Appendix D), with a total treatment capacity of 32 m^3/d
- The full-scale MBR design does not promote denitrification (there is any anoxic chamber nor recirculation pump)
- The permeate would be used for fertilizing, generating savings in the hotel irrigation costs
- Permeate mean nutrient concentrations, obtained during the pilot operation, were considered to calculate the fertilization savings.
- The current fertilizers used by the hotel are ammonium sulfate and triple superphosphate
- For calculating the chemicals consumption due to membrane cleaning, the requirements of the pilot MBR plant were taken as a reference, despite the fact that the full-scale membranes would be from a different supplier and would have a different configuration
- The permeate pipeline would be connected to the existing irrigation system.

5.3. Full-scale MBR costs

5.3.1. Capital expenditure (CAPEX)

The capital expenditure (CAPEX) was calculated considering the building costs of the plant and a 47% of overhead due to taxes, unforeseen events and engineering costs. Most prices were obtained from the local market or estimated from literature data. The total investment cost calculated was 120.804 USD. Table 30 summarizes the items taken into account for the investment cost:

Table 30 CAPEX calculations.

CAPEX						
Item	**Life (years)**	**Amount**	**Unit**	**USD/unit**	**Total Cost (USD)**	**References & Comments**
FS Membranes	5-10	80	m^2	-	21,587	International manufacturer
Tank floor	30	1,11	m^3	1357	1,504	Uruguay construction market
Tank walls	30	3,19	m^3	1357	4,322	Uruguay construction market
Land preparation and levelling	30	35	m^2	93	3,266	Uruguay construction market
Air blower	5	2	unit	5500	11,000	Importing company in Uruguay
Fine bubble diffuser	10	9	unit	43	387	Importing company in Uruguay
Coarse bubble diffuser	10	9	unit	30	271	Estimation according to fine bubble diffuser cost
Suction pump	10	3	unit	654	1,962	(Tomei Water Solutions)
Sludge pump	10	2	unit	300	600	Estimation according Uruguay market
Permeate pump	10	2	unit	1158	2,316	Estimation according Uruguay market
Permeate storage tank (40m3)	20	1	unit	16000	16,000	Local manufacturer
Subtotal 1					**63,215**	**-**
Electro technical	15%				9,482	(DeCarolis et al. 2007)
Plumbing and mechanical	15%				9,482	(DeCarolis et al. 2007)
Subtotal 2 (Building cost)					**82,180**	**-**
Taxes	22%				18,0804	Uruguay Value Added Tax (VAT)
Unforeseen	10%				8,218	(Haase 2017)
Engineering	15%				12,327	(Haase 2017)
Total investment cost					**120,804**	**-**

It should be noticed that no equalization tank, influent pump nor sludge tank were included in the list because those items are already available in the existing wastewater treatment plant and are suitable as well for the MBR plant. The lifespan of the units were estimated according to the values reported by Atanasova et al. 2017 and Haase 2017. More detailed information about the costs calculations can be found in Appendix E.

5.3.2. Operation expenditure (OPEX)

The operation and maintenance costs were also calculated (Table 31):

Table 31 OPEX calculations.

OPEX			
Item		**Total cost (USD/year)**	**References & Comments**
Energy consumption		**5,135**	
Air blowers (kWh/year)	26280		Appendix E
Pumping (KWh/year)	13748		Appendix E
Electrical Energy Cost (USD/kWh)	0.13		National electric power administration
Sludge Disposal		**383**	
Sludge generation (m3/year)	102		Appendix D
Sludge disposal cost (USD/m3)	3.77		Colonia Sludge Truck Company
Maintenance		**503**	
Mechanical maintenance (USD/year)	266		2,5 % of mechanical building cost (Haase 2017)
Electrical maintenance (USD/year)	237		2,5 % of electrical building cost (Haase 2017)
Chemicals		**98**	
Consumption of NaOCl (L/year)	76		1 cleaning/10 days was considered
Cost of NaOCl 100% (USD/L)	1.29		Price provided by local drugstore
Manpower		**2,505**	
Working hours (h/year)	288		1 hour per day, 6 days a week
Operator wage(USD/h)	8.7		Cost estimated according mechanical operators in the hotel industry
Total OPEX		**8,623**	

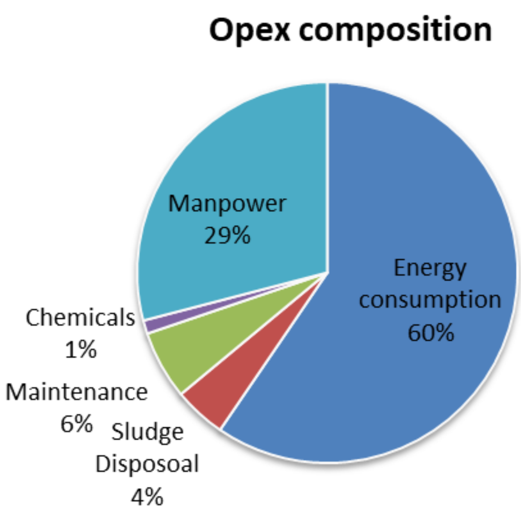

Figure 37 Operation costs and its components.

It can be seen that the most relevant parameter is the energy consumption, due to the air requirement for membrane scouring, which was calculated in Appendix D and is 39% higher than the aeration demand for the biological treatment.

Taking into account only the OPEX, the cost of the permeate would be 1,3 USD/m^3, which is lower than the cost of the drinking water supplied by the national water agency (1,9 USD/m^3).

Detailed information about the energy consumption calculations is mentioned in Appendix E.

5.4. Economic discussion

To begin with, if MBR energy operating costs are compared to the ones of the actual treatment plant, the MBR operation would consume 39% more energy, presenting an increase of 2.004 USD/year. However, this only represents 0,8% of the total energy costs of the hotel.

When comparing the sludge disposal costs theoretically, the conventional treatment would generate 4 times more sludge than the MBR plant, costing around 1.148 USD more per year.

Regarding fertilizers savings, 478 kg /year and 78 kg/year of ammonium sulfate and triple superphosphate respectively could be saved if permeate irrigation is conducted. In terms of money, this only represents 270 USD per year, which is negligible when comparing it to the total operating costs of the MBR plant (around 3%).

A key factor that is not being quantified when comparing the alternatives is the environmental benefit of implementing MBR technology.

Nowadays, the treatment plant complies with the national environmental regulations and no further treatment is required. However, if following the international trend, DINAMA applies stricter regulations, the hotel would have to invest and improve its wastewater treatment plant in the near future.

Moreover, considering the international trend for water reuse, the worldwide environmental awareness and the national interest of achieving sustainable tourism, MBR technology in hotels may also improve their company's name and increase their popularity, generating economic benefits.

All in all, in this case where the hotel already has a wastewater treatment plant that complies with the national regulation, MBR technology is not economically feasible due to its investment costs and its higher operating costs. Nevertheless, considering the water quality of the permeate, the potential water savings and its environmental benefits, and the fact that the cost of the permeate is cheaper than the cost of drinking water, MBR implementation should be considered and promoted in future projects since it may be a competitive alternative.

CHAPTER 6

Conclusions and recommendations

6.1. Conclusions

During this research, the performance of a pilot-scale MBR was tested in the hotel sector with the objective of studying its suitability for achieving wastewater reuse for irrigation. This project aimed to promote and contribute to the sustainable development of the tourism industry in Uruguay, following the international and national trend.

Regarding the MBR operation, the following conclusions were reached:

- The MBR technology has sensitive operational parameters (such as the membrane pressure) and requires skilled manpower for its operation.
- Without external inoculation, the startup of the system can take more than two months if it is fed with hotel wastewater. Nevertheless, removal efficiencies are not compromised during this period. Moreover, neither sludge waste nor chemical cleaning may be needed at this stage.

The next conclusion to be drawn is that MBR technology is a reliable solution for ensuring an excellent water quality in the effluent. 93% and 94% mean removal efficiencies were achieved regarding organic matter (total COD) and ammonium respectively. Except from phosphorous, all permeate parameters complied with the Uruguayan standards for discharging wastewater into water bodies.

Moreover, the permeate also accomplished WHO and UNEP requirements for water reuse for irrigation in urban areas. If EPA guidelines are considered, the permeate should only be irrigated in restricted areas. The water presented excellent aesthetic qualities (it would be accepted by the guests) and has no health risks. Nevertheless, signs should be installed along the golf course areas to prevent visitors for drinking the reused water.

From an agronomic point of view, the permeate water presents no risks to the soil and can unrestrictedly be used for turfgrass irrigation.

Furthermore, the permeate could also contribute to the golf course fertilization, since its nutrient load would cover 100% the phosphorous demand and 55% the nitrogen demand of the total golf course greens.

Considering the economic aspects of MBR technology, in this case, it was not an economically feasible solution due to its high energy demands and investment costs. Plus, the lack of a tight environmental regulation hinders its promotion and implementation.

Nevertheless, MBR technology is a suitable alternative that should be taken into account in future projects in the hotel industry since it has been proved that it achieves better water qualities than a conventional wastewater treatment, it could minimize the use of fertilizers, decreases hotel environmental impacts and promotes a sustainable tourism development.

Finally, regarding the hotel water streams:

- If the hotel effluent is to be used for irrigation, further steps should be added in the treatment line to decrease the content of solids, organic matter, and pathogens.
- The hotel irrigation water can have higher pathogen content than the international recommended values. To prevent any health threat, irrigation should be done at night and warning signs should be installed in the golf course.

6.2. Recommendations

Firstly, it is highly recommended to operate the reactor for a longer period of time in order to evaluate the permeate quality and the MBR operational parameters (such as flux and permeability) under a steady state operation and the designed MLVSS concentration.

Phosphorous removal techniques should also be studied to find a suitable solution for achieving a phosphorous concentration of 5 mg/L in the permeate and reach the watercourse discharge national standards.

Finally, an in-depth agronomic research should be conducted to evaluate the long-term impact of the permeate irrigation on greens and to design a sustainable irrigation plan. On-site instrumentation and underground water monitoring should be implemented to prevent surface water bodies pollution, regarding nutrients, pathogens, and salts.

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Appendices

Appendix A Flowrate and pressure registers

Date	Flow (L/h)	Flow (m3/d)	HRT (h)	Mean suction P (bar)	Jp Flux (L/h.m2)	Operation Permeability (L/h.m2.bar)	Observations
08/01/2018	106,8	2,56	11,2	0,13	16,2	128,3	Operation started 18 hrs.
09/01/2018	101,7	2,44	11,8	0,16	15,4	99,3	-
10/01/2018	104,7	2,51	11,5	0,04	15,9	452,4	Pressure dropped significantly, but flow remained the same.
11/01/2018	86,7	2,08	13,8	0,03	13,1	434,7	Pressure dropped significantly, but flow remained the same.
12/01/2018	67,8	1,63	17,7	0,12	10,3	85,6	The permeate valve was adjusted, pressure increased and flow remained the same.
13/01/2018	68,0	1,63	17,7	0,13	10,3	78,2	-
14/01/2018	68,4	1,64	17,5	0,15	10,4	68,6	-
15/01/2018	67,1	1,61	17,9	0,17	10,2	58,6	-
16/01/2018	76,9	1,84	15,6	0,20	11,6	58,0	Blackout late at night
17/01/2018	-	-	-	-	-	-	No operation
18/01/2018	139,1	3,34	8,6	0,18	21,1	116,0	System was turned on
19/01/2018	74,6	1,79	16,1	0,18	11,3	61,7	-
20/01/2018	75,3	1,81	15,9	0,19	11,4	61,0	-
21/01/2018	-	-	-	-	-	-	PC reset. No operation
22/01/2018	131,5	3,16	9,1	0,11	19,9	177,2	-
23/01/2018	97,2	2,33	12,4	0,05	14,7	276,1	Pressure dropped radically to 50-40 mbar, flow was of the same order than previous day
24/01/2018	103,8	2,49	11,6	0,02	15,7	666,6	-
25/01/2018	55,0	1,32	21,8	0,02	8,3	524,6	Fail in reverse pump
26/01/2018	45,8	1,10	26,2	0,02	6,9	407,4	Fail in reverse pump
27/01/2018	0,4	0,01	-	0,03	-	-	Fail in reverse pump
28/01/2018	0,0	0,00	-	0,02	-	-	Fail in reverse pump
29/01/2018	70,1	1,68	17,1	0,16	10,6	64,6	Adjustment of permeate valve
30/01/2018	92,1	2,21	13,0	0,18	14,0	76,8	-
31/01/2018	78,0	1,87	15,4	0,19	11,8	63,7	-
01/02/2018	67,4	1,62	17,8	0,19	10,2	53,9	-
02/02/2018	68,6	1,65	17,5	0,19	10,4	54,7	-

Date	Flow (L/h)	Flow (m3/d)	HRT (h)	Mean suction P (bar)	Jp Flux (L/h.m2)	Operation Permeability (L/h.m2.bar)	Observations
03/02/2018	68,6	1,65	17,5	0,18	10,4	57,7	-
04/02/2018	58,5	1,40	20,5	0,18	8,9	48,9	-
05/02/2018	71,3	1,71	16,8	0,16	10,8	66,1	Leak in reverse pump was observed and fixed
06/02/2018	62,5	1,50	19,2	0,13	9,5	71,9	-
07/02/2018	52,8	1,27	22,7	0,12	8,0	65,6	-
08/02/2018	52,8	1,27	22,7	0,12	8,0	66,7	
09/02/2018	-	-	-	-	-	-	PC reset. No operation
10/02/2018	-	-	-	-	-	-	PC reset. No operation
11/02/2018	52,8	1,27	22,7	0,13	8,0	61,6	-
12/02/2018	52,8	1,27	22,7	0,13	8,0	61,6	-
13/02/2018	52,8	1,27	22,7	0,14	8,0	57,2	-
14/02/2018	-	-	-	-	-	-	No operation-Blackout
15/02/2018	74,6	1,79	16,1	0,19	11,3	60,0	-
16/02/2018	46,2	1,11	26,00	0,20	7,0	35,4	Pmin reached: PLC error, because P>-400 mBar. System was off for a couple of hours but then was turned on
17/02/2018	64,0	1,54	18,8	0,17	9,7	58,5	-
18/02/2018	-	-	-	-	-	-	Blackout and no WWTP staff
19/02/2018	182,0	4,37	6,6	0,16	27,6	171,3	At 10:05 the equipment was on again
20/02/2018	102,2	2,45	11,7	0,18	15,5	85,2	-
21/02/2018	63,8	1,53	18,8	0,25	9,7	38,7	-
22/02/2018	67,1	1,61	17,9	0,27	10,2	37,2	-
23/02/2018	70,0	1,68	17,1	0,30	10,6	35,6	-
24/02/2018	95,5	2,29	12,6	0,31	14,5	47,4	-
25/02/2018	76,3	1,83	15,7	0,32	11,6	36,4	-
26/02/2018	68,5	1,64	17,5	0,33	10,4	31,7	-
27/02/2018	66,3	1,59	18,1	0,34	10,0	29,5	Last day of operation

Appendix B Analysis result tables

Hotel effluent and irrigation water samples				
Date Identification	20-feb Irrigation water	28-feb Effluent	01-mar Effluent	01-mar Irrigation water
pH	7,65	7,24	7,24	7,79
Temperature (°C)	24,9	27,3	27,4	25,4
DO (mg/L)	-	0	0	6,48
COD (mg/L)	41,5	187	150	20,1
Soluble COD (mg/L)	-	55,2	49,6	-
BOD_5 (mg/L)	32	-	-	-
TN (mg N/L)	<5	38,4	42,4	1,00
Soluble TN (mg N/L)	-	-	30	-
TKN (mg/L)	-	-	-	-
NO2 (mg NO2-N/L)	0,100	0,127	0,131	0,032
NO3 (mg NO3-N/L)	0,3	<5	<5	<0,5
NH4 (mg NH4-N/L)	0,3	32	30	0,1
PO4 (mg PO4-P/L)	3	12,4	12,4	<0,5
TP (mg PO4-P/L)	12,0	21,2	23,2	0,3
Soluble TP (mg PO4-P/L)	-	-	11,2	-
TSS (mg/L)	47,47	91,46	59,20	3,65
VSS (mg/L)	4,49	21,11	41,60	0,35
Turbidity (FAU)	53	97	74	6,0
Turbidity (NTU)	7,8	-	-	2,0
EC (dS/m)	-	0,822	0,879	0,436
TDS (mg/L)	-	534	571	283
Ca (mg/L)	-	-	-	21
Mg (mg/L)	-	-	-	6,7
Na (mg/L)	-	-	-	48
SAR	-	-	-	2,3
Sulfate (mg/L)	16,9	-	-	-
Bicarbonate (mg CaCO3/L)	154	-	-	-
Chloride (mg/L)	19,2	-	-	22,3
Boron (mg/L)	-	-	-	<0,15
E.Coli (CFU/100mL)	<1800	-	-	-
Fecal Coliforms (CFU/100mL)	<1800	-	-	-
Total Coliforms (CFU/100mL)	3,50E+05	-	-	-

Influent and permeate samples									
Date	8-Jan	12-Jan		18-Jan		22-Jan		29-Jan	
Identification	Inf.	Inf.	Perm.	Inf.	Perm.	Inf.	Perm.	Inf.	Perm.
pH	6,50	6,66	6,50	6,65	6,59	6,54	6,38	6,47	5,90
Temperature (°C)	-	-	-	-	-	-	-	-	-
OD (mg/L)	-	-	-	-	-	-	-	-	-
COD (mg/L)	>1500	600	83	390	30	350	35	460	25
Soluble COD (mg/L)	-	-	-	-	-	260	-	290	-
BOD5 (mg/L)	-	-	-	-	-	-	-	258	-
Soluble BOD5 (mg/L)	-	-	-	-	-	-	-	171	-
TN (mg N/L)	-	51	32	36,0	16	43,0	16	45,0	29
Soluble TN (mg/L)	-	-	-	-	-	38	-	37	-
TKN (mg N/L)	-	-	-	-	-	-	-	49,2	-
NO2 (mg NO2-N/L)	-	-	-	-	-	1	<1	0,18	0,23
NO3(mg NO3-N/L)	-	-	-	-	-	0,5	15	3	20
NH4+ (mg NH4-N/L)	39	39	2,3	23	1,7	32,64371	0,21	26	2,4
PO4- (mg PO4-P/L)	23,25	12,3	10,2	10,8	12,1	14	12,1	12	11,4
TP (mg PO4-P/L)	23,9	12,3	9,8	13	12,4	14	12,3	12	11,8
Soluble TP (mg/L)	-	-	-	-	-	-	-	10,2	-
Turbidity (FAU)	-	-	-	-	-	-	-	-	-
Turbidity (NTU)	-	-	-	-	-	-	-	-	-
TSS (mg/L)	-	-	-	-	-	-	-	-	-
VSS (mg/L)	-	-	-	-	-	-	-	-	-
Boron (mg/L)	-	-	-	-	-	-	-	-	-
Ca (mg/L)	-	-	-	-	-	-	-	8,8	-
Mg (mg/L)	-	-	-	-	-	-	-	3	-
Na (mg/L)	-	-	-	-	-	-	-	37	-
SAR	-	-	-	-	-	-	-	2,7	-
Bicarbonate (mg CaCO3/L)	-	-	-	-	-	-	-	-	-
Chloride (mg/L)	-	-	-	-	-	-	-	-	-
Cl2 residual (µg/L)	-	-	-	-	-	-	-	-	-
Sulfide (mg/L)	-	-	-	-	-	-	-	-	-
E.Coli (CFU/100mL)	-	-	-	-	-	-	-	9,20E+05	-
Fecal Coliforms (CFU/100mL)	-	-	-	-	-	-	-	9,20E+05	-
Total Coliforms (CFU/100mL)	-	-	-	-	-	-	-	1,60E+06	-

Date Identification	5-Feb Inf.	 Perm.	11-Feb Inf.	 Perm.	15-Feb Inf.	 Perm.	20-Feb Inf.	 Perm.	1-Mar Inf.	 Perm.
pH	6,55	7,37	6,54	6,40	6,49	6,90	6,65	7,30	6,53	6,45
Temperature (°C)	29,0	28,6	-	-	25,3	26,6	28,4	28,9	27,5	27,2
OD (mg/L)	-	-	-	-	-	-	-	-	0,0	4,5
COD (mg/L)	340	42,0	510	12	310	28,2	341	25,1	456	26,2
Soluble COD (mg/L)	-	-	228	-	225	-	215	-	355	-
BOD5 (mg/L)	-	26	-	-	275	-	-	7,5	-	-
Soluble BOD5 (mg/L)	-	-	-	-	180	-	-	7,4	-	-
TN (mg N/L)	51	24	65	22	54	32	42	34	68	20
Soluble TN (mg/L)	-	-	54	-	49	-	32	-	62	-
TKN (mg N/L)	-	-	-	-	-	-	-	-	-	-
NO2 (mg NO2-N/L)	0,131	>7	0,081	0,34	0,158	1,59	0,173	1,17	0,145	0,53
NO3(mg NO3-N/L)	0,5	6	0,3	15	0,5	23	0,5	23	0,4	14
NH4+ (mg NH4-N/L)	44	7,1	47	1,3	46	1,5	36	2,1	54,2	2
PO4- (mg PO4-P/L)	11,8	10,7	12,2	12,3	11,8	13,6	14,8	12,8	12,2	12,5
TP (mg PO4-P/L)	12,4	11,2	19,4	12,2	12,1	13,4	20	13,5	12,2	12
Soluble TP (mg/L)	-	-	13,3	-	10,8	-	14,2	-	11,6	-
Turbidity (FAU)	-	4	-	3	-	4	-	3	-	2
Turbidity (NTU)	-	-	-	-	-	-	-	2,1	-	0,8
TSS (mg/L)	-	0	-	0	42,70	0	58,56	0	49,43	0
VSS (mg/L)	-	0	-	0	30,06	0	47,97	0	36,55	0
EC (ds/m)	-	-	-	-	-	0,555	-	0,693	-	0,611
Boron (mg/L)	-	-	-	-	-	-	-	-	-	<0,05
Ca (mg/L)	-	-	-	-	-	-	-	-	-	-
Mg (mg/L)	-	-	-	-	-	-	-	-	-	-
Na (mg/L)	-	-	-	-	-	-	-	-	-	-
SAR	-	-	-	-	-	-	-	-	-	-
Bicarbonate (mg CaCO3/L)	-	-	-	-	-	-	-	52,8	-	-
Chloride (mg/L)	-	-	-	-	-	41,9	-	51,9	-	-
Cl2 residual (µg/L)	-	-	-	-	-	<16	-	<16	-	-
Sulfide (mg/L)	-	-	-	-	-	<0,2	-	-	-	<0,1
E.Coli (CFU/100mL)	-	-	-	-	9,20E+05	17	-	110	9,20E+05	18
Fecal Coliforms (CFU/100mL)	-	-	-	-	9,20E+05	33	-	110	9,20E+05	20
Total Coliforms (CFU/100mL)	-	-	-	-	>1600 000	240	-	1600	9,20E+05	1300

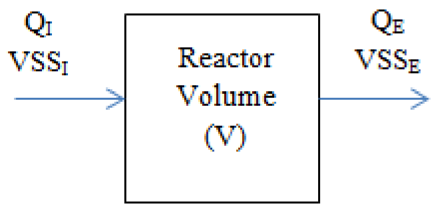
Mixed liquor samples											
	05-ene	**08-ene**	**12-ene**	**18-ene**	**22-ene**	**29-ene**	**05-feb**	**11-feb**	**15-feb**	**20-feb**	**28-feb**
pH	7	6,5	6,5	7,12	6,9	5,09	6,6	6,2	6,67	6,96	6,42
Temperature (°C)	-	-	27,6	-	-	24,5	27,5	-	23,4	29,2	26,7
DO (mg/L)	-	-	-	-	-	-	3,83	-	-	-	3,58
TSS (mg/L)	419	277	189	602	1036	734	1797	1644	1709	1356	2686
VSS (mg/L)	386	253	111	277	968	593	1381	1089	1037	1146	2377

Appendix C Calculations for biomass growth estimation in the MBR during the start up

To estimate the production of biomass during the start-up, VSS mass balance equation was solved for batch operation. The following considerations were taken into account:

- Constant volume in the reactor
- Constant substrate concentration (BOD_5) in the reactor
- No VSS content in the permeate (VSS_E=0 g/m^3)
- Influent flowrate the same as the effluent
- The initial biomass concentration in the reactor was 253 mg/L, since it was the first day of continuous operation (Xto= 253 mgVSS/L)

VSS MASS BALANCE:



$$\frac{\partial Mx}{\partial t} = \frac{V\partial X}{\partial t} = Q_I VSS_I + r_g V - Q_E VSS_E$$

being:

Mx the biomass mass in the reactor (g)
X the biomass concentration (gVSS /m^3)
t time of operation (days)
Q_I and Q_E the influent and effluent flow rate (m^3/d)
VSS_I and VSS_E the VSS concentration in the influent and effluent respectively (g/m^3)
V= reactor volume (m^3)
r_g= biomass growth rate (gVSS/m^3.d), that according to Henze et al. 2008 defined as:

$$r_g = \mu_{max} \frac{S_S}{K_S + S_S} X - bX$$

where:
S_S is the substrate concentration (g/m^3)
μ_{max} is the maximum growth rate of biomass (gVSS/gVSS.d)
Ks is substrate half saturation constant (gCOD/m^3)
and b is specific biomass decay rate (VSS/gVSSd).

Solving the differential equation, the expression obtained is:

$$t = \frac{V}{\left(\mu_{max}\frac{S_S}{K_S + S_S} - b\right)} \ln \frac{Q_I VSS_I + Xt\left(\mu_{max}\frac{S_S}{K_S + S_S} - b\right)}{Q_I VSS_I + Xt_0\left(\mu_{max}\frac{S_S}{K_S + S_S} - b\right)}$$

Solving that expression for achieving a final concentration of 2400 $gVSS/m^3$, and taking into account the influent characterization, the retention time needed should be 15 days. The parameters used for doing the calculation are presented below:

Influent Characterization (mean values)	
COD total (mg/L)	417
COD soluble (mg/L)	262
COD suspended (mg/L)	155
BOD5 (mg/L)	258
Ntotal (mg/L)	51
Ammonia-N (mg/L)	39
Ptotal (mg/L)	14,2
Ortho-P (mg/L)	12,7
TSS (mg/L)	50
VSS (mg/L)	38
Temperature (°C)	26,5
Operational conditions	
Xto (mgVSS/L)	253
Vrector (m3)	1,2
Flow (m3/d)	1,87
Kinetic Parameters	
Umax20	0,24
umaxT	0,51
Ks	27,00
KsT	57,39
b20	0,24
bT	0,29

Appendix D Full scale MBR design

To make the economic evaluation of the project, a full scale design of the MBR system was done following the procedure and equations in Garcia 2016.

To be conservative, the MBR system was designed for the maximum influent load (highest flowrate and concentrations). Two trains of treatment were proposed in order to have operational flexibility and to contemplate the lower flowrates in winter. The design temperature was the minimum water temperature during winter: 12°C.

The membranes picked for the design were the FS50 from Kubota manufacturers (Kubota 2018).

Membrane design features, influent characterization and calculations are presented below:

Influent characterization (mean values)		
Influent Flow Rate (Qi)	32	m3/d
Influent Soluble Unbiodegradable COD (Si)	163,2	mg/L
Influent Biodegradable COD (Sbi)	285,6	mg/L
Influent Particulate Unbiodegradable COD (Xi)	61,2	mg/L
Total Suspended Solids (TSS)	58,6	mg/L
Volatil Suspended Solids (VSS)	48,0	mg/L
Influent Total Kjeldahl Nitrogen (Nti)	65	mg/L
Effluent Total Kjeldahl Nitrogen (Nte)	2	mg/L
Effluent Nitrate (Nne)	50,6	mg/L
Temperature	12	°C
Influent Biomass Concentration	0	mg/L
Design Conditions		
True Yield (Y_{HV})	0,45	gVSS/Gcod
Specific biomass decay rate (b_H)	0,24	gVSS/gVSS-d
Endogenous residue fraction (f_H)	0,2	-
COD/VSS ratio (f_{CV})	1,48	mgCOD/mgVSS
Inorganic content of active biomass (f_{iOHO})	0,15	gISS/gVSS
Yield coefficient Nitrification (Y_A)	0,12	gVSS/gFSA
Endogenous respiration rate nitrification (b_A) @ 20°C	0,08	1/d
Half saturation coefficient nitrification (Kn) @ 20°C	0,74	mgFSA/L
Maximum specific growth rate (μ_{Am}) @ 20°C	0,75	1/d
MBR $_{MLTSS}$	10000	mg/L
Dissolved Oxygen (DO)	2	mg/L
Oxygen saturation constant,Ko	0,5	g/m3

O2,sat@12°C	10,78	mg/L
Membranes feature		
Type	FS50	
Flux (LMH)	17,0	L/m2-h
Total Membrane Area	0,80	m2
Membranes/Cassette	50	units/smu
Tank Depth	2,0	m
Cassette large	0,8	m
Cassette width	0,6	m
Distance btw cassette	1,01	m
Distance cassette-wall	0,762	m
Volume/cassette	1,05	m3

STEP 1: membrane sizing

		Comments
Which area is required?		
A (m^2)	78	
How many membranes?		
Number	98	
How many cassettes?		
SMU	2	
Configuration		
Trains	2	In low season only operates one
SMU/train	1	
Final membrane area (m2)	**80**	
Net flux (LHM)	**16,6**	
Volume of each membrane tank		
Depth (m)	2,0	If it were higher, each train of the system would be twice the total required aerated volume
Width (m)	1,0	Consider 10 cm between membrane and tank walls
Large (m)	2,1	Consider 75 cm between membrane and tank walls
Total Volume (each tank) (m3)	**4,2**	
Water volume displaced by cassettes(m3)	0,7	

Useful volume for biological activity (m3)	**3,5**

STEP 2: aerated tank design to achieve nitrification

2.1.Correct kinematic parametres and constants by temperature (T=12°C)

$$\mu_{A,m(T)} = \mu_{A,m(20)}(1.07)^{(T-20)}$$
$$K_{n(T)} = K_{n(20)}(1.053)^{(T-20)}$$
$$b_{A(T)} = b_{A(20)}(1.04)^{(T-20)}$$
$$b_{H(T)} = b_{H(20)}(1.029)^{T-20}$$

μ_{Am}@12°C	0,44	1/d
Kn@ 12°C	0,49	mgFSA/L
b_A@ 12°C	0,06	1/d
bH@12°C	0,19	1/d

2.2. Calcualte SRT

$$Specific\ Growth\ Rate\ (\mu_A) = \left(\frac{\mu_{A,m} N_{te}}{K_n + N_{te}}\right)\left(\frac{DO}{K_o + DO}\right) - b_A$$

$$\frac{1}{SRT} = Specific\ Growth\ Rate\ (\mu_A)$$

$$Safety\ factor = 1.3$$

SRT= 6 days

3.Calculate fractions of biomass within the reactor

-MX_{BHv}: mass of active microorganisms in the bioreactor (g VSS)

$$MX_{Bv} = Q_I * Sbi \frac{Y_{hv}\ SRT}{1 + b_H SRT}$$

-MX_{EHv}: mass of endogenous residue in the bioreactor (g VSS)

$$MX_{EH,OHO} = f_H b_H MX_{BV}\ SRT$$

-MX_{Iv}: mass of influent unbiodegradable matter in the bioreactor (g VSS)

$$MX_{IV} = QiMX_{IV}\ SRT$$

-MX_N: mass of nitrifying bacteria (g VSS)

$$MX_N = \frac{Q_i * (NO_X = N_c) Y_A * SRT}{1 + b_A * SRT}$$

-MX_V: mass of volatile suspended solids in the bioreactor (g VSS)

$$MX_V = MX_{BH,v} + MX_{EH,v} + MX_{IV} + MX_N$$

-MX_{IO}: mass of inorganic matter in the bioreactor (g ISS)

$$MX_{IO} = Q_i * X_{IOI} * SRT + f_{iOHO} * MX_{Bv}$$

-MX_T: total solids in the reactor (g TSS)

$$MX_T = MX_V + MX_{IO}$$

MX_{BHv} (kg)	11,44
MX_{EHv} (kg)	2,62
MX_{Iv} (kg)	7,90
MX_N (kg)	0,94
MX_V (Kg)	15,00
MX_{IO} (Kg)	22,90
MX_T (Kg)	3,74

4.Reactor Volume (aerobic)

$$V_t = \frac{M_{XT}}{X_T} * 1.3$$

V=3,46 m^3

5.Sludge Production and waste flow (Q_w)

$$FX_t = \frac{M_{XT}}{SRT}$$

$$Q_W = \frac{FX_t}{X_t}$$

Qw= 444 L/d

6.Nitrification achieved (NOx)

The mass of nitrate obtained by nitrification (FNOx, kg/d) was calculated using the following equation:

$$FNOx = Q * NOx = QNti - QNte - 0.12FXv \ ;$$

FNOx=1,7 kg/d

where FXv is the biomass production per day and NOx is the concentration of nitrogen that was nitrified.

STEP 3: AIR REQUIRMENTS FOR OPERATION

For calculating the theoretical oxygen demand (FO, kg/d), the expression proposed by Judd (2006) was used, taking out the denitrification term:

$$FO = Qi\ (Sbi - Sbe) - 1.42\ FX_v + 4.33\ Qi\ NO_x$$

Considering that all the BOD_5 would be consumed in the reactor (Sbe=0 mg/L), the value obtained was 12, 9 kg O_2/d.

The oxygen consumption was converted to aeration capacity (OC), taking into account an alpha factor of 0,7 (mean value suggested by Jong (2017)):

$$OC = \frac{FO}{\alpha}\left(\frac{O_{2,sat})}{O_{2,sat} - O_{2,design}}\right) = 22{,}7\ kgO2/day$$

Considering the depth of the reactor (2m), an O_2 transfer efficiency of 5% per meter of water and converting the units to volume of air, the air demand for the biological activity in the reactor is 34,6 m^3/h.

In order to prevent the membranes for easily getting clogged and to enhance the filtration, extra air must be supplied to the membranes surface. The specific aeration demand based on membrane area (SADm) is an empiric parameter calculated through operation and determines the scouring air flow required for proper operation. To estimate the net air consumption of the full scale MBR, a conservative SADm of 0.6 Nm^3/m^2h was used (based on the values reported in Judd (2006)).

The air demand value calculated for the total membrane area was: 48, 0 m^3/h.

To sum up, the aeration demands calculated in this section are:

Air demand for aerobic treatment (m3/h)	34,5
Air demand for membrane scouring (m3/h)	48,0
Total air demand (m3/h)	**82,6**

Appendix E Economic considerations

This appendix details the information provided in chapter 6 and how the main costs were calculated or estimated.

Building costs considerations are described in the following table:

Item	Explanation
Membranes	The cost of the membranes was provided by the international manufacturer (Memos filtration). An overhead of 60% was taken into account for importation (suggested by a local customs broker).
Aeration tank	Two concrete tanks (2,4 x1,0 x 2,1 m), sharing one wall were considered. The floor is of 20 cm and the walls 12 cm. The height of the tank is 40 cm higher than the water level to prevent any contingency.
Land conditioning	An area of 35 m^2 was estimated for the MBR plant. The price presented (93 USD/m^2) includes 30 cm of soil excavation and two layers of compacted calcareous tuff.
Air Blower	The capacity of the air blower was calculated with the total air demand of the system and taking a safety factor of 1,2. The price and energy consumption of the unit was consulted with a local supplier.
Fine bubble diffusers	9” membrane diffusers were selected, with a mean flow rate of 6Nm3/h each. To calculate the number of diffusers, the flow rate was adjusted by temperature and a safety factor of 1.2, to contemplate possible air leaks in the installation. One extra diffuser was considered for backup. Cost and features were consulted with a local supplier
Coarse bubble diffusers	Diffusers of 8Nm3/h were selected from SSI Aeration.One extra diffuser was considered for backup. The price was estimated at 30% cheaper than the fine bubble diffusers.
Permeate and backwash pump	One pump per train and a backup unit were taken into account. The price and the power consumption were obtained from Tomei Water Solutions. A 50% of overhead on the price was assumed for importation.
Sludge pump	One sludge pump was considered for operation and another one for backup. The flow required is 20L/min. The power of the pump and its price were estimated and consulted with local engineers.
Influent pump	No investment cost was considered since the current influent pump of the hotel can be used. The energy consumption was taken from DAB Water Technology..
Permeate tank	A covered glass fiber tank was selected (cheaper, faster to build and smaller footprint than concrete tanks). Everyday irrigation

	was contemplated; being the total volume of the tank 35 m^3. Its cost was provided by a local manufacturer.
Permeate pump	One hour irrigation during the night was planned, to have lower energy costs and to prevent the guests from being in touch with the irrigation water. Around a 32 m^3/hour flowrate and 30 m height were selected and used for calculating the power of the pump. The cost of the pump was consulted with a local manufacturer.

Assumptions and information taken into account for the energy consumption estimation are presented below:

Energy consumption calculations			
Air Blower	Power (Kw)	3	To be conservative, it was assumed that the air blower worked full time. The aeration regime could be optimized once the plant is operating, according to the results obtained.
	Working hours/year	8760	
Influent pump	Power (Kw)	1	It was estimated that in low season, the influent pump consumes half the power since a frequency driver is connected to the pump
	Working hours/year	5490	
Suction/Backwash pump	Power (Kw)	0,55	Two pumps work together in summer and only one in winter.
	Working hours/year	10980	
Sludge pump	Power (Kw)	0,2	In low season the sludge pump works half the time.
	Working hours/year	5490	
Permeate pump	Power (Kw)	5,2	One hour per day in high season and half an hour in low season
	Working hours/year	229	

In all cases, the power consumption of the products was the nominal value that appeared in the product's specifications.