Chapter 12
CAPEX and OPEX Evaluation of a Membrane Bioreactor Aiming at Water Reuse

Leonardo Dalri-Cecato, André Aguiar Battistelli, and Flávio Rubens Lapolli

Abstract The main discussion regarding the large-scale application of membrane bioreactors in effluent treatment is related not to their efficiency, but to the expenditures involved both in their implementation and operation. However, information on the costs of this technology is reported inconsistently, unevenly, and without periodicity, negatively affecting its credibility and the quantification of its economic impacts. Given that, this study consisted of the application of the life cycle cost evaluation methodology to evaluate the capital and operational expenditures of a membrane bioreactor designed to be implemented in Santa Catarina/Brazil, with a capacity to treat 6060 m^3 d^{-1} (50,000 inhabitants), and aimed at the production of reclaimed water. The estimated implementation costs considered the expenditures regarding the acquisition of membranes, area purchase, and construction. The operational costs survey considered membrane replacement, energy consumption, sludge disposal, and the payment of employees. Values equivalent to R$3363.08 m^{-3} d or R$407.61/inhabitant were estimated regarding the capital expenditure, and R$0.63 m^{-3} or R$2.10 per kg of BOD removed were estimated regarding the operational expenditures of the proposed wastewater treatment plant, which agree with other studies addressing the costs of membrane bioreactors. In addition, the proposed system tends to be competitive in producing reclaimed water, since the cost of its treatment is considerably below the amount charged for the drinking water in the region concerned.

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Introduction

Membrane bioreactor (MBR) technology consists of the combination of the classic wastewater treatment process of conventional activated sludge and the physical process of membrane separation (Judd and Judd 2011). MBR operation delivers advantages related to the high quality of the generated effluent and the consequent opportunity to perform water reuse. Also, the technology allows for operation with higher sludge ages and effluents with elevated suspended solid concentrations, resulting in reduced sludge production and its required disposal and necessary building areas (Metcalf and Eddy 2003; Le-Clech 2010; Kootenaei and Aminirad 2014).

However, despite the reported advantages, Judd (2017) points out that the main discussion regarding the application of MBR in wastewater treatment is not related to its efficiency, but in fact to the costs inherent in the process. The author also observes that, among the numerous possible approaches for raising and categorizing the expenses linked to an enterprise, the distinction between implementation (CAPEX—Capital Expenditure) and operation (OPEX—Operational Expenditure) costs is often employed. The information yielded by this methodology is often confronted with economic data regarding activated sludge technology, facilitating comparative analysis (Young et al. 2012; Iglesias et al. 2017; Judd 2017).

The number of scientific studies related to MBR cost estimation matches the lack of economic data about the technology. Judd (2017) conducted a bibliometric study on the main topics addressed in researches related to MBR and found that only 0.5% of the documents published between 2001 and 2016 addressed marketing and cost issues. Also, existing information on membrane bioreactor costs is reported inconsistently, unevenly, and without periodicity (Pirani et al. 2012; Judd 2017). Thus, the lack of credibility and availability of such data is harmful in ascertaining the economic viability of this technology (Verrecht et al. 2010).

Given the lack of information about this subject, it is necessary and relevant to expand knowledge about MBR, combining studies regarding their efficiency and operation with research that considers the economic viability of real-scale deployment for different situations and locations. In the Brazilian scenario, research of this nature is scarce. Thus, a greater emphasis in this field of knowledge would help, for instance, in the decision-making process regarding the type of sewage treatment applied in a given situation, as well as in the increase of Reclaimed Water Producing Plants (RWPP), which represent a promising alternative to current water crises (Dalri-Cecato et al. 2019).

In this regard, Life Cycle Cost Analysis (LCCA) emerges as a relevant tool to assist in accounting for the costs of environmental technologies. Rebitzer et al. (2003) highlight LCCA as an essential tool to introduce an economic point of view in decision-making processes concerning projects of environmental interest, such as choosing which type of treatment to apply in a Wastewater Treatment Plant (WWTP). Also, it is relevant to mention the studies of Dhillon (2010), who applies LCCA to a waste treatment plant, in addition to the works conducted by Koul and John (2015) and Bhoye et al. (2016), both of which address applications of LCCA in WWTP.

In this context, this study aimed to apply LCCA methodology as an aid to the survey and discussion of CAPEX and OPEX data from an MBR designed to be implemented in Santa Catarina/Brazil, addressing the production of reclaimed water.

Methodology

This research follows the methodology and principles presented by Dalri-Cecato et al. (2019). The following topics feature the criteria considered during the design and cost assessment of the evaluated membrane bioreactor.

Membrane Bioreactor

Cost simulation was performed considering an aerobic MBR designed to operate in a continuous flow regime, located in the state of Santa Catarina/Brazil, serving a population of 50,000 people. The arrangement chosen consisted of membrane modules submerged in a filtration tank separated from the biological system, as indicated by Metcalf and Eddy (2014). The implementation of a pre-denitrification step was considered in the project to reduce the effects of eutrophication and clogging during reuse practice (Von Sperling 2005; Marecos and Albuquerque 2010). Furthermore, an equalization tank was designed, enabling stabilization of incoming flow, reducing costs concerning the acquisition of membrane modules necessary to meet peak flow rates (Metcalf and Eddy 2014; Judd and Judd 2011).

LCCA of the MBR

Survey and cost assessment of the proposed MBR followed the principles of the LCCA methodology. The models proposed by Dhillon (2010), Koul and John (2015), and Bhoye et al. (2016) were adapted to address the situation of this study adequately.

CAPEX

The proposed MBR CAPEX survey considered the main contributors to the cost of installing membrane bioreactors, characterized by land acquisition (Judd 2017; Young et al. 2012), membrane acquisition (Judd 2017), and construction-related expenditures (Young et al. 2013), as presented in Eq. 1:

$$CAPEX = M + L + CC \tag{1}$$

In which:
M—membrane acquisition costs;
L—land acquisition costs;
CC—construction costs.

OPEX

The contributors to MBR operation cost considered in the OPEX calculation were energy consumption, periodic membrane replacement (Young et al. 2013; Iglesias et al. 2017; Judd 2017), employee's payroll (Young et al. 2012, 2013), and waste sludge management (Lo et al. 2015), as presented in Eq. 2. Data was compiled to represent the annual cost of operation.

$$OPEX = E + MR + P + SD \tag{2}$$

In which:
E—energy costs;
MR—periodic membrane replacement costs;
P—employee's payroll costs;
SD—sludge disposal costs.

Results and Discussion

Membrane Module

The membrane module chosen to compose the proposed MBR was Zeeweed 500D-370 from Suez Water Technologies & Solutions, with hollow-fiber and inward-flow characteristics, specially designed for use in MBR. Table 1 presents the module's main characteristics.

The application of Cassette 48M was predicted in order to organize the modules in the filtration tank. Produced by the same company, the chosen cassettes include the components necessary for membrane aeration distribution. Table 2 presents relevant information concerning 48M Cassette.

Table 1 Zeeweed 500D-370 membrane module characteristics

Parameter	Value
Material	PVDF
Nominal pore size (μm)	0.04
Length (m)	0.049
Height (m)	2.198
Width (m)	0.844
Volume (m^3)	0.091
Filtering area (m^2)	34.4

Source SUEZ (2016)

Table 2 48M cassette characteristics

Parameter	Value
Length (m)	2116
Height (m)	2561
Width (m)	1745
Volume (m^3)	9456

Source SUEZ (2017)

Membrane Bioreactor

The proposed MBR sizing followed the procedures presented by Dalri-Cecato et al. (2019).

Table 3 presents the main design parameters used to size the evaluated MBR.

Table 3 Project parameters for the proposed MBR

Input parameter	Value
Contributing population	50.000 inh.
Per capita water consumption	150 L/inh d
Sewage return rate	0.8
Average sewage flow (Q_{avg})	6.060 m^3 d^{-1}
Infiltration flow	1% Q_{avg}
Average BOD_5 concentration affluent to the biological tank	300 mg/L
Average COD concentration affluent to the biological tank	600 mg/L
Average TNK concentration affluent to the biological tank	45 mg/L
Affluent BOD load	1.818 kg/d
Sludge age	40 d
VSS concentrations in the biological tank	10 g/L

Table 4 Treatment units and respective dimensions

Treatment unit	Effective volume (m^3)	Height (m)	Surface area (m^2)
Biological tank	1.530	4.5	340
Equalization tank	945	4.5	210
Anoxic tank	387	4.5	86
Membrane tank	189	3.0	63

Table 5 Dimensions and operations of the filtration tank

Parameter	Value
Number of modules	375
Number of cassettes	8 + 1
Operation/Relaxation (min/min)	9/1
Critical flux ($L/m^2\ h^{-1}$)	25
Operation flux ($L/m^2\ h^{-1}$)	21
Volume (m^3)	189
Surface area (m^2)	63
Width (m)	3
Length (m)	21
Height (m)	3

Table 4 presents the main treatment units and their respective dimensions.

Table 5 synthesizes essential information about the dimensions and operation of the filtration tank.

CAPEX

Membrane Acquisition

Given the membrane module chosen, its supplier was contacted in order to collect data concerning the technology's cost. It was possible to obtain information regarding the market value of its square meter of filtering area (7 $ ft^{-2} or 75.35 $ m^{-2}, in July 2018), as well as the proportion between the purchase cost of the membrane modules and cassettes (70% and 30%, respectively, in August 2018), considering a fully populated 48M module.

Table 6 presents cost data per square meter of filtering area, proportions of values between modules and cassettes, as well as additional relevant information regarding the purchase of membranes required for the proposed MBR. Since the chosen product

Table 6 Summary of costs related to membrane acquisition

Parameter	Value
ZW 500D	75.35 $.m^{-2}[a]
Membrane cost/total cost	70%[b]
Cassettes cost/total cost	30%[b]
Number of MBR modules	375
MBR total membrane area	12.900 m^2
Membranes customs value	$971980.17
Cassettes customs value	$469882.99
Exchange rate	4.0687[c]
Converted membranes' customs value	R$3954695.72
Converted cassettes' customs value	R$1.911.812,90
Total converted customs value	R$5866508.62

Source [a]Contact with supplier in July 2018
[b]Contact with supplier in August 2018
[c]USD to BRL exchange rate (PTAX) in 08/27/2018 (BCB 2018)

Table 7 Taxes charged over membranes acquisition

Tax	Rate (%)	Value (R$)
II	14	821311.21
IPI	8	535025.59
PIS	2	123196.68
COFINS	10.65	624783.17
ICMS SC	17	1632578.67
Total taxes		3736895.31

must be imported, it is necessary to consider the taxes levied on NCM 84219999 (Brazil 2018b), considering the destination of the purchase in the state of Santa Catarina (1996), as presented in Table 7.

Furthermore, membrane installation costs were set as 10% of the total converted customs value, as indicated by Young et al. (2013), totaling R$586650.86. The final membranes acquisition cost, considering acquisition of modules and cassettes, taxes, and installation, was R$10190054.79 or 203.80 R$.inh^{-1}.

Land Acquisition and Civil Construction

The survey of land acquisition and construction costs considered data from historical and statistical series obtained from the Brazilian Institute of Geography and Statistics (IBGE).

Table 8 presents data related to the average cost of one square meter for Santa Catarina in 2018.

Table 8 Average land acquisition cost in Santa Catarina (SC)

Month (2018)	Average land cost in SC (R$.m^{-2})
January	1200.63
February	1207.52
March	1212.15
April	1211.98
May	1210.22
June	1228.70
Average	1211.87

Source IBGE (2018a)

Table 9 Building materials cost in SC

Month (2018)	Building materials cost in SC (R$.m^{-2})
January	562,92
February	569,81
March	571,22
April	571,05
May	571,23
June	576,06
Average	570,38

Source IBGE (2018b)

The purchase of an area equivalent to 0.15 m^2 inh^{-1} was considered in the calculation (Iglesias et al. 2017), resulting in 7.500 m^2 of land necessary for the installation of the proposed MBR. This yields a cost of R$9089.000, equivalent to 181.79 R$.inh^{-1}.

The construction cost, characterized by the sum of expenditures on building materials and labor, was estimated in the station's constructed area. Compiled historical data on average building materials and labor costs are presented in Tables 9 and 10, respectively.

Table 10 Average labor cost in SC

Month (2018)	Average labor cost in SC (R$.m^{-2})
January	637.71
February	637.71
March	640.93
April	640.93
May	638.99
June	652.64
Average	641.49

Source IBGE (2018c)

A constructed area of 2.036 m^2 was estimated, taking into consideration the sum of the surface areas of the treatment units presented in Table 4, in addition to a 30% margin for the construction of supplementary WWTP facilities. In this context, the costs related to the acquisition of construction materials and labor were calculated to be R$1161430.16 or 23.23 R$.inh^{-1} and R$1306213.14 or R$26.12 inh^{-1}, respectively. Therefore, the total cost of construction estimated was R$2467643.30 or 49.35 R$.inh^{-1}.

CAPEX Summary

Table 11 presents the summary of costs related to the proposed MBR CAPEX, including absolute and relative costs.

The estimated CAPEX of R$3588.56 m^{-3}d or 434.93 R$ inh^{-1} is consistent with surveys conducted by Iglesias et al. (2017) at MBR stations in Spain, that analyzed the costs of MBR compared to extended aeration activated sludge and other reuse water production technologies. According to the authors, the CAPEX of stations with a capacity between 5000 and 10,000 m^3 d^{-1} operating with (a) extended aeration activated sludge; (b) activated sludge with subsequent coagulation, sand filters, and disinfection; (c) activated sludge followed by membrane filtration; and (d) MBR is equivalent to 600, 715, 1030, and 960 € m^{-3}d, respectively. Moreover, the authors point out the influence of WWTP capacity on deployment costs, highlighting CAPEX values for flows between 1000 and 2000 m^3 d^{-1} to be around 420–650 € inh^{-1}, while for installations above 10,000 m^3 d^{-1} the cost is reduced to 94 € inh^{-1} due to the economy of scale.

The most significant individual contribution to the proposed MBR CAPEX was related to the acquisition of membranes and cassettes (47%), similar to the result found by Verrecht et al. (2010) (46.9%). The second most significant portion of CAPEX was related to land acquisition, representing 42% of the total value. Construction costs were relatively low, equivalent to 6% for hiring labor and 5% for acquiring construction materials, totaling 11%, while other surveys estimated contributions between 33 and 35% (Verrecht et al. 2010; Young et al. 2013). However, a better representation of this parameter can be achieved by increasing the cost of civil

Table 11 CAPEX summary for the proposed MBR

Parameter	Absolute cost	Relative cost	
CAPEX	(R$)	(R$.$inh^{-1}$)	(R$.$m^{-3}$d)
Membranes and Cassettes	10190054.79	203.80	1681.53
Land	9089000.00	181.78	1499.83
Construction materials	1161430.16	23.23	191.66
Labor	1306213.14	26.12	215.55
Total CAPEX	21746698.09	434.93	3588.56

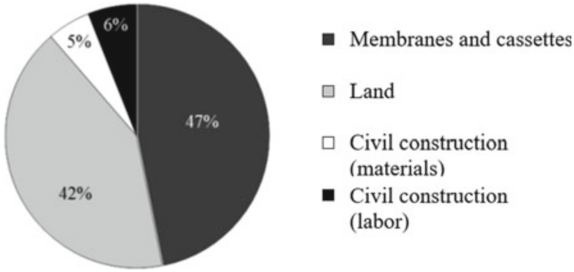

Fig. 1 Individual contribution of CAPEX parameters

construction to consider the transportation of materials and soil, earthmoving, foundations, projects, and hiring of other employees required for the construction of the WWTP.

Figure 1 displays the distribution of the contributions of each evaluated CAPEX parameter.

OPEX

Energy Consumption

Studies show that for optimized MBR systems it is possible to achieve energy consumption values between 0.4 and 0.6 kWh m^{-3}, with perspectives of consumption reduction due to new research findings (Itokawa et al. 2014; Xiao et al. 2014; Iglesias et al. 2017; Judd 2017; Krzeminski et al. 2017). In this context, the total energy consumption of 0.5 kWh m^{-3} was adopted for the proposed MBR.

The determination of the adopted kWh cost took into consideration the rates charged by CELESC (Santa Catarina's energy enterprise) for projects related to sanitation. Thus, Group A, subgroup A4—Water, Sewage, and Sanitation's blue hourly peak hour rates were considered, characterizing the most unfavorable scenario for this type of consumer. Under these circumstances, the charges amount to R$0.45593485/kWh, in addition to the incidence of 25% ICMS (CELESC 2018), which is the tax applied to the movement of goods and services.

Hence, it was possible to estimate an annual electricity cost equal to R$635020.59 or R$0.29 m^{-3}. However, it should be noted that the rates charged by energy companies vary according to availability and demand, and for this reason, more advantageous electricity costs can be achieved.

Periodic Membrane Replacement

Total membrane replacement was considered to take place after ten years of operation (Cote et al. 2012), to be conducted with the same cost as the purchase and installation

Table 12 Salary for WWTP operators in SC

	Value (R$)	
Company		Source
SAMAE Orleans	2979.07	SAMAE ORLEARNS (2018)
VISAN Videira	2306.55	VISAN (2018)
SAMAE Blumenau	1180.32	SAMAE BLUMENAU (2018)
SAMAE São Bento do Sul	2912.58	SAMAE SÃO BENTO DO SUL (2018)
SAMAE Urussanga	2822.83	SAMAE URUSSANGA (2018)
Results		
Average Gross Salary	2440.27	
Taxes	1708.59	
Total per month per employee	4148.46	
Total per year for 4 employees	199126.03	

of original membrane modules considered in this project. It should be noted that this is a one-off operating expense, that for comparison purposes it was diluted over the lifetime of the station (considered to be 20 years), resulting in an annual cost of R$392317.11 or R$0.18 m^{-3}.

Cost of Employees

Table 12 presents the results obtained from the salary survey conducted to estimate the cost of employees, characterized by the payment of the WWTP operators. The surveyed payments refer to the year 2018. 70% of taxes were considered in addition to the actual salary, which must be paid by the employer.

A team of four operators was considered for the proposed WWTP (Young et al. 2012). Thus, the estimated annual cost with employees was R$199126.03 or R$0.09 m^{-3}.

Sludge Disposal

The cost of sludge disposal in landfills was calculated by collecting data regarding the unit costs for sludge management, annual generation of sludge (in tons), and total yearly sludge disposal cost of ten WWTPs operated by the Santa Catarina Water and Sanitation Company (CASAN), as shown in Table 13.

Table 13 WWTP sludge disposition costs in SC

WWTP	Unit cost (R$/ton)	Tons (ton/year)	Annual cost (R$)
Insular	218.64[a]	10.020	2190772.80
Canasvieiras		3.854	842638.56
Lagoa da Conceição		360	78710.40
Araquari Centro	281.00	158	44398.00
Canoinhas	329.00	150	49350.00
Indaial	267.00	100	26700.00
Braço do Norte	298.00	180	53640.00
Criciúma	247.00	2.700	666900.00
Laguna	350.00	220	77000.00
Chapecó	340.00	840	285600.00
Weighted average	232.25		

Source CASAN (2018a, b)
[a]Transportation costs not included

Given the adopted sludge age (40 days), a sludge disposal of approximately 43 m^3 d^{-1} or 430 kgTSS d^{-1} was estimated. Considering centrifugal dewatering, with 95% solids captured and 20% solids concentration in the sludge disposed (Andreoli et al. 2007), a sludge production of approximately 727 tons/year was stipulated, equivalent to R$168847.33/year or R$0.08/m^3.

OPEX Summary

Table 14 presents the summary of costs related to the proposed MBR OPEX.

The estimated OPEX of R$0.63/$m^3$ or R$2.10/kg of removed BOD is in line with studies carried out by Iglesias et al. (2017). According to the authors, the OPEX of stations with a capacity of 5000–10,000 m3d^{-1} operating with (a) extended aeration activated sludge; (b) activated sludge with subsequent coagulation, sand filters, and

Table 14 OPEX summary for the proposed MBR

Parameter	Absolute cost	Relative cost
OPEX	(R$/year)	(R$/$m^3$)
Energy consumption	635020.59	0.29
Periodic membrane exchange	392317.11	0.18
Employees	199126.03	0.09
Sludge disposition	168847.33	0.08
Total OPEX	1395371.64	0.63

disinfection; (c) activated sludge followed by membrane filtration; and (d) MBR amounts to 0.22, 0.31, 0.40, and 0.32 €/m^3, respectively, including the expenditure on sludge disposal. The authors also indicate values between 0.5 and 18 €/kg BOD when evaluating the OPEX of the studied MBR.

The WWTP energy consumption represented 46% of the operating costs, while other studies indicate contributions around 27–34% (Lo et al. 2015), 41% (Iglesias et al. 2017) and 79.6% (Verrecht et al. 2010). The cost relative to periodic exchange of membranes agrees with studies performed by Lo et al. (2015), representing 28% of the contribution.

The proposed MBR operators' payment represented 14% of OPEX, similarly to that estimated by Young et al. (2013) (15%). Lo et al. (2015) mention participation percentages equal to 14; 5.6 and 2.8% for stations of different dimensions. Brepols et al. (2010) show values of 24%, considering a capacity related to 10,000 people.

Finally, sludge disposal represented 12% of OPEX, being lower than the data presented by Iglesias et al. (2017) (16%), Verrecht et al. (2010) (17.9%), and Brepols et al. (2010) (21%). It is noteworthy that the cost assessment performed in this study included the classic form of sludge disposal (landfill). However, alternative options to dispose this waste may be considered, such as agricultural use, composting or anaerobic digestion.

Figure 2 displays the distribution of the contributions of each evaluated OPEX parameter.

The OPEX cost of R$0.63/m^3 of treated effluent is considerably below the rates applied in Santa Catarina for drinking water, where for uses with consumption greater than 10 m^3/month in industrial, public, and micro and small commerce categories, one must pay R$10.7866/m^3 (CASAN 2018a, b). This result is in line with the research conducted by Young et al. (2013) which highlights the competitiveness of MBR with activated sludge technology for situations where high nutrient removal rates are required, or reuse is desired.

It is important to emphasize that the costs of transport and chlorination should be considered when performing water reuse, which would increase OPEX. However, the transport of reused water to the desired location increases the overall OPEX by 0.02 to 0.04 €/m^3 (Iglesias et al. 2017), and chlorine disinfection represents less than 3% of total costs of operation (Verrecht et al. 2012). Therefore, the application of

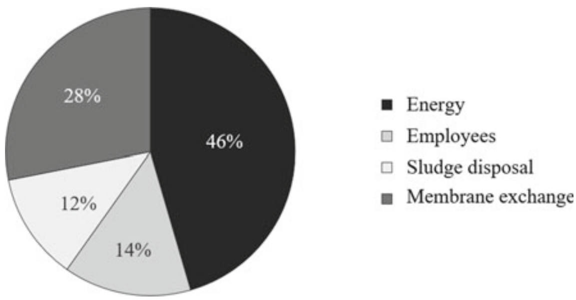

Fig. 2 Individual contribution of OPEX parameters

MBR in reclaimed water production in Santa Catarina presents itself as an attractive choice, both from an economic and environmental point of view, since the state has industrial centers distributed in different regions, as well as public and commercial demands for water.

Final Remarks

The survey of the implementation costs for the proposed MBR presented CAPEX values equal to R$3588.56/$m^3$ d^{-1} or R$434.93/inh., which agree with other studies addressing the costs of the same technology. The most significant individual contribution to CAPEX is related to the acquisition of membranes and cassettes (47%), followed by land acquisition (42%) and civil construction (11%).

The results obtained from the survey of operating costs also agreed with data found in the literature, presenting values equivalent to R$0.63/$m^3$ or R$2.10/kg of removed BOD. The most considerable individual contribution to the system's OPEX was characterized by energy consumption (46%), followed by periodic membrane exchange (28%), employee payment (14%) and sludge disposal (12%). Finally, results showed that the proposed system is competitive concerning the production of reclaimed water, as its OPEX is considerably lower than the price for drinking water in the studied region.

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