ELUCIDATING THE RELATIVE ENVIRONMENTAL SUSTAINABILITY OF ANAEROBIC MEMBRANE BIOREACTOR (ANMBR) DEVELOPMENT PATHWAYS

BY

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THESIS

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ABSTRACT

The current approach to municipal wastewater treatment relies on aerobic-based technologies, which are energy-intensive and thus inconsistent with the trend in which broader environmental impacts are becoming increasingly important in decision-making. Anaerobic membrane bioreactors (AnMBRs), as an emerging anaerobic technology, are gaining popularity because of their potential to achieve energy-positive treatment and to achieve a high quality effluent. This thesis aims to explore the full-scale design and the environmental sustainability of AnMBRs. Key steps and decisions concerning the design of AnMBRs were synthesized into a roadmap.

Life cycle assessment (LCA) was conducted for multiple AnMBRs linking various design and operational decisions to broader environmental impacts. This methodology was developed as a MATLAB-based LCA model to predict the environmental impacts categorized by the U.S. EPA’s Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). The LCA results demonstrate that AnMBRs designed as a continuous stirred-tank reactor (CSTR) with a submerged membrane configuration are likely to be the most energy-intensive and also the least environmentally-sustainable, while the addition of granular activated carbon (GAC) into the AnMBR of the same reactor type and configuration would circumvent the principal source of life cycle impacts (gas sparging) and achieve the most environmental sustainable design. The significance of the roadmap developed in this study is its nature as a blueprint for the future research development and design of AnMBR technology.
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Wastewater treatment plant (WWTP) designs have been focused on protecting human health and the local aquatic environment (receiving streams and local bodies of water) for many years [1]. Due to the fact that there is an increasing awareness of broader environmental impacts for which human are responsible and want to take into consideration as well, this is not suitable for the 21st century. In order to advance environmental sustainability, the paradigm of municipal wastewater treatment designs is shifting to conservation of energy and reduction in environmental impacts while maintaining effluent quality [1, 2].

However, traditional aerobic-based municipal wastewater treatment plants (e.g. activated process) are energy-intensive [2, 3]. The total energy consumption of the current municipal wastewater treatment plants account for about 3% of the US electrical energy demand [4]. Not only does high energy consumption lead to high costs, but also numerous environmental impacts such as global warming potential.

As a result, these emerging criteria in municipal WWTP design creates opportunities for the development of anaerobic treatment processes. In addition to opportunities for reduced energy demand, biodegradable organic matter can be converted to methane, hydrogen or electricity with anaerobic processes, which can be recovered to offset the energy consumption of WWTPs [1, 3, 5].

Nevertheless, using only methane-producing anaerobic processes for municipal wastewater treatment has a major challenge, which is to date, anaerobic processes haven not generally been able to meet the effluent quality required for municipal wastewater treatment [6, 7]. Due to the fact that anaerobic processes are commonly used to treat high-strength industrial wastewater, the treatment of low-strength municipal wastewater could cause the system fail to retain sufficient biomass since anaerobes have much slower growth rates than aerobes
Also, anaerobes do not generally aggregate like activated sludge flocs [6]. In addition, wastewater treated by anaerobic process could also have odor problems in the effluent, which requires further polishing treatment [7]. Thus, a robust design of anaerobic processes is needed to solve these problems.

Anaerobic membrane bioreactors (AnMBRs) are such a technology that couples anaerobic processes with membrane filtration. AnMBRs have the ability to both recover biogas and produce high quality effluent [8]. In addition, the presence of a membrane provides a sufficient solids retention time for anaerobic biomass to achieve high concentrations and thus improve effluent quality [3, 8, 9].

The treatment performance of AnMBRs could be compromised, however, due to membrane fouling, which needs to be taken into consideration when adopting this technology for wastewater treatment. Therefore, membrane fouling mitigation methods needs to be applied. Typically, gas sparging is used in submerged AnMBRs, whereas a high cross-flow velocity is maintained for cross-flow AnMBRs. Nevertheless, this is not always the case. For example, the addition of granular activated carbon (GAC) to AnMBRs could also effectively prevent fouling without gas sparging [10]. Furthermore, adding a post-treatment for the effluent of the anaerobic reactor is also an option. An example is up-flow aerobic sponge trickling filter. Due to the direct exposure of freely-hanging packing material to the atmosphere, this aerobic reactor is able to eliminate aeration while providing a polishing purpose [11].

Being an emerging treatment technology, AnMBRs have not been implemented by the wastewater treatment industry. Although there is research focusing on the treatment performance of bench-scale reactors, little is known about whether or not AnMBRs are environmentally friendly and could achieve energy positive/neutral [12].

The objective of this work is to develop a quantitative tool for the assessment of the environmental sustainability of full-scale AnMBR designs, and to leverage this tool to develop a roadmap for full-scale AnMBR designs. The outcome of this work is a MATLAB-based life cycle assessment (LCA) model for AnMBRs linking to design and operational decision space. The LCA model helps determine and compare the environmental impacts of different AnMBR designs, and also helps identify the key sources of their environmental impacts. Furthermore, the potential of these AnMBRs to achieve energy-neutral/positive wastewater
treatment is also analyzed.
CHAPTER 2
BACKGROUND

2.1 LCA of Municipal WWTPs

In order to study and advance the environmental sustainability of WWTPs, life cycle assessment (LCA) is often used to quantify their environmental impacts [13, 14]. There have been a fair amount of studies of LCAs focusing on various types of WWTPs including traditional treatment technologies, advanced or emerging technologies [8, 15, 16], and also decentralized or small-scale systems.

LCAs can be used to investigate the dominant environmental impact sources ("hot spot") within a treatment system. Operational energy consumption is reported to cause most of the environmental burdens within a WWTP [17, 18, 19, 20, 21], especially global warming and acidification [18]. In addition, the energy demand is related to soluble and particulate substrate of wastewater [22]. Comparative LCAs are often used to identify the most environmentally-friendly system among multiple treatment systems [8, 15, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34].

2.2 Disparities in LCA Studies

Published studies are not consistent in their use of LCA for wastewater treatment. The inconsistencies in LCAs are summarized in the followings aspects.

First of all, a consistent choice of functional unit would ensure the comparability between different LCA studies for WWTPs since comparisons should be made on a common basis or the same function [35, 36]. However, different functional units are utilized in literature including per volume of wastewater treated [8, 13, 16, 23, 24, 29, 37], per capita or population
equivalent [33, 34], or per mass of chemical oxygen demand (COD) removed [17, 26].

Second, the system boundary of any LCA should be defined based on reasoned judgments and assumptions because the cut-off criteria of the system boundary are crucial for the degree of confidence in the LCA results [35]. However, the system boundary definition in some literature is subjective and the inclusion or exclusion of a process or material in life cycle inventory analysis is sometimes biased [38]. For example, construction phase is included in some LCAs of WWTPs [8, 24, 27] but excluded in others. Similarly, sludge treatment/disposal is also included in some studies [13, 17, 39] but not in others.

Also, the choice of life cycle impact assessment methodologies is not consistent. There are several different methodologies such as TRACI, CML, Eco-indicator 99, EDIP, EPS, etc. Some studies found consistency among these methodologies [40], while others noticed significant disparities among them [41]. An impact assessment methodology defines the environmental mechanism and characterization model that relate the LCI results to impact categories of different methodologies [36]. However, the characterization model and assumptions made behind each methodology remains unknown, leading to the unmeaningful comparisons among LCAs that utilize different methodologies.

Furthermore, some studies [42, 43] convert midpoint impact indicators to endpoint indicators by conducting normalization and weighting. Midpoint indicators are less biased but also less favorable to decision making, while endpoint indicators are more comprehensible but the normalization or weighting of different environmental impacts could be biased [44, 45]. However, it is possible to achieve different endpoint indicator results based on the same midpoint indicator values because weighting is based on value choices instead of being scientifically based [36]. As a result, the choice of whether to use midpoint or endpoint indicators is debatable.

2.3 Anaerobic Membrane Bioreactor

Membrane bioreactors (MBRs) is an emerging technology where conventional reactors are coupled with membrane filtration processes [8]. Typical MBRs are split into two categories: aerobic and anaerobic MBRs.
MBRs are gaining popularity in wastewater treatment, and most MBRs employed in full-scale WWTPs are aerobic membrane bisectors (AeMBRs). MBRs has the following advantages compared to traditional treatment processes such as the activated sludge (AS) process. First, due to the elimination of secondary clarifiers, MBRs has a smaller footprint than AS process [3, 8]. The compactness of MBRs also leads to lower capital cost. Second, MBRs separates solids retention time from hydraulic retention time, which can provide adequate solids retention time (SRT) for the slow growing anaerobic biomass [3, 8, 9]. Third, MBRs can produce a high quality effluent [3, 8], which allows MBRs to be employed in water reuse schemes [46]. Despite these advantages, one commonly cited drawbacks of MBRs is its high cost compared to traditional treatment processes; not only are the initial capital costs of membrane modules high, but they also lack a long life span, which leads to replacement costs down the road. However, this drawback may prove insignificant in upcoming years as multiple sources have noted that membrane cost has been dropping progressively over the last decade [46, 47].

However, AeMBRs has several notable drawbacks. First of all, AeMBRs requires high energy consumption [8, 9]. Hospido et al. pointed out that the electricity consumption of AeMBRs is about 0.4-1 kWh/m³, which is very high and on par with the 0.3-0.4 kWh/m³ of AS process [8]. The high energy consumption is mainly due to membrane fouling control [8]. Second, AeMBRs have very high solid yields [9], which leads to more sludge disposal.

On the other hand, due to the increased popularity of anaerobic processes, anaerobic membrane bioreactors (AnMBR) has potential for municipal wastewater treatment. AnMBRs has the following advantages over AeMBRs: first, as an anaerobic process, no aeration is needed, which reduces energy consumption. Second, energy can be recovered from methane-rich biogas produced in AnMBRs. AnMBR was reported to have a high energy recovery rate of about 9.7 kJ/g – COD degraded [3]. Third, AnMBRs can be operated at low hydraulic retention time (HRTs) [9], which leads to smaller reactors and saves on capital costs.

However, using AnMBRs to treat municipal wastewater still has a few challenges. First, AnMBRs is not as developed as AeMBRs, which has already been employed in municipal WWTPs for quite some time [9], and to date, AnMBRs has rarely been utilized for full-scale treatment [46, 48]. AnMBRs also produces a higher mixed liquor concentration than
AeMBR do, which is more likely to cause membrane fouling [47]. Furthermore, even though aeration is eliminated for AnMBRs, the gas sparging process used to mitigate fouling is energy-intensive. Finally, as far as membrane fouling mechanism is concerned, less work has been done on AnMBRs than on AeMBRs [46].

2.3.1 AnMBRs of Different Configurations

An AnMBR can be considered as the combination of an anaerobic reactor and membrane modules. Several types of anaerobic reactors can be used in AnMBRs. Continuously stirred tank reactor (CSTR) is the most common choice for AnMBR, as well as for AeMBR [46, 47]. However, the drawback of using CSTRs is that the membrane is exposed to bulk solids concentration [47]. The second reactor type is anaerobic filters, which is considered better because a lower concentration of COD is entering the membrane [47]. There are other types of reactors used in AnMBRs mentioned in literature including upflow anaerobic sludge blank (UASB) [46, 49], EGSB [46, 47, 50], and fluidized bed [46, 51], but these types of reactors are not typically used.

In terms of configurations, AnMBRs can be divided into three types. The first type is submerged AnMBRs, which has membrane modules submerged in an anaerobic reactor. Submerged AnMBRs are vacuum-driven, which means a vacuum is used to draw effluent through the membrane. Flat sheet and hollow fiber membrane modules are usually preferred for submerged AnMBRs [47]. There are some advantages of this configuration. First, it is a more conventional configuration because the majority of the existing full-scale aerobic MBRs are of this configuration [52]. Second, some studies reported submerged AnMBRs had a lower capital and operating costs compared to other configurations [9]. However, there are some disadvantages, the biggest of which is that it requires gas sparging for fouling control, which is energy-intensive. Second, submerged AnMBRs need to be operated at a much lower flux, which leads to a larger membrane area [9].

The second type is external cross-flow AnMBRs, where the membrane modules are placed outside of the anaerobic reactor. Unlike submerged AnMBRs, external cross-flow AnMBRs are pressure-driven, and tubular membrane modules are preferred over other types of mem-
brane modules [47]. One of the advantages is that gas sparging is usually not required, which reduces energy consumption; Shoener et al. reported that fouling mitigation is less energy-intensive for this configuration [3]. Second, external membrane modules makes it easier for membrane cleaning and replacement [9]. On the other hand, although gas-sparging is not used here, a high cross-flow velocity ($2-4 \text{ m/s}$) needs to be maintained to scour membrane surface for membrane fouling control and also to provide high pressure for filtration [9]. Second, because the high cross-flow velocity creates a high shear force, and some studies reported that high shear forces could disrupt cells, which would reduce biomass biological activity and thus decrease treatment performance [9, 47, 48]. High shear force may also lead to more significant fouling because of the decrease in floc size [47, 48].

The third type is side-stream AnMBRs, which has membrane modules submerged in a tank separate from the anaerobic reactor. This configuration is less common than the previous two; it provides a compromise between AnMBRs of the submerged and the external cross-flow configurations.

2.3.2 Membrane Fouling Control

There are several ways to control membrane fouling. First of all, AnMBRs can be operated in a filtration-relaxation (F-R) cycle, where backwashing is conducted every few F-R cycles [53]. Relaxation is carried out by ceasing permeation and backwashing is achieved by reversing the filtration flow [54]. F-R cycle is typically composed of 8-15 minute filtration with 45 second to 2 minute relaxation [50, 54, 55]. Backwashing is typically conducted every 1 to 10 F-R cycle for 30-50 seconds [54, 55].

Second, chemicals, including acids/bases/oxidants, are often used for membrane cleaning during CIP (cleaning in place) and COP (cleaning out of place) [9], where acids (e.g. $HCl$, $H_2SO_4$, and citric acid) are used to remove inorganic foulants [47]; bases (e.g. $NaOH$) and oxidants (e.g.$H_2O_2$ and $NaOCl$) are used to remove organic foulants. CIP is usually conducted weekly or monthly, whereas COP is conducted yearly. Often times, these chemicals are used in combination. For example, Lin et al. conducted a weekly CIP with 500 mg/L $NaOCl$ and 2000 mg/L citric acid, and a COP twice a year with 1000 mg/L $NaOCl$ and
2000 mg/L citric acid, along with 0.1 kg NaOH/kg COD removal [48].

Aside from adding chemicals into reactors, for submerged configurations, gas sparging is used for fouling control, where biogas produced in anaerobic process is used to scour membrane surface. Studies show that fouling rate decreases when gas sparging rate increases from 10 to 25L/m²−min [56]. However, there is a limit for gas sparging rate beyond which the increase in sparging rate would have little added benefit [47]. Furthermore, intermittent sparging can be used instead of continuous sparging to save energy, and has only a small influence in the increase in transmembrane pressure (TMP) [57]. For external cross-flow configurations, a high cross-flow velocity is maintained to limit foulant buildup [46]. Some studies show that there exists a threshold of cross-flow velocity beyond which the increase in cross-flow velocity will not improve fouling control [58]. To avoid energy-intensive fouling controls, powdered activated carbon (PAC) or granular activated carbon (GAC) can be added in anaerobic reactors [10].

### 2.3.3 Operating Parameters

Hydraulic retention time (HRT) is directly related to reactor size, which means the decrease in HRT will lead to a lower capital cost [9, 46, 47]. For AnMBRs, HRT can go as low as 3 hours. Some reported that typical HRT is about 8 - 12 hours [48], others reported a longer HRT of 12-17 hours [9]. Studies show that HRT has little to no effect on AnMBR performance above 15 degrees C [46, 49, 50, 59, 60]. For submerged MBRs, HRT can go as low as 4 hours and can still achieve 97% COD removal [9]. Some studies show that there should be a lower limit of HRT due to membrane fouling concerns [46].

A long solids retention time (SRT) allows anaerobic biomass to have sufficient time to grow, and thus increases COD removal rate [9, 46]. However, longer SRT may lead to a lower permeate flux [46, 47, 61, 62, 63]. Also, longer SRT results in higher concentrations of SMP and EPS, which may contribute to membrane fouling [46, 63].

Studies show that typical flux range of AnMBRs is 7-10 L/m²−h [9], which is low compared to the 25 L/m²−h of AeMBRs [48]. When operated at a lower flux (7 L/m²−h), AnMBRs can be operated for a long time without significant flux loss. However, when
operated at a higher flux (10 to 12 $L/m^2 - h$), AnMBRs will show significant fouling, which is uncontrollable even by gas sparging [64].

As for organic loading rate, a typical range is 0.3 - 12.5 $kg - COD m^3/day$ [47]. Some studies show that organic loading rate can go as high as 25 $kg - COD m^3/day$ in most common cases, and 16 $kg - COD m^3/day$ with PAC added in the reactor [9].

Membrane modules need to be replaced when there is a significant irreversible loss in flux and foulants cannot be removed by fouling control methods. A typical membrane module can last about 6-7 years [47], which is short compared to the life span of other infrastructure.

2.3.4 Prospect and Challenge of AnMBRs

As an emerging treatment technique, AnMBRs has yet to be widely employed in low/medium-strength municipal wastewater treatment plants. Nevertheless, due to the advantages mentioned above, the use of AnMBRs should grow [47]. There are still some challenges of AnMBRs to overcome.

First of all, a large portion (30-50%) of methane produced during the anaerobic process is dissolved in water and will be lost in effluent [3, 46]. To achieve the energy neutral/positive goal, how to fully exploit methane by recovering dissolved methane is a problem that needs to be solved. Existing dissolved methane recovery techniques include post-treatment aeration, degassing membranes, and down-flow hanging sponge reactors [46]. Dissolved methane recovery also requires energy, and whether it is worth it to recover the dissolved methane should be further studied.

2.4 Research Focus

The existing LCA studies from literature have a numerous limitations. First of all, life cycle inventory analyses involved in the LCAs are not comprehensive. Environmental impacts from construction phase are sometimes ignored without much justification. The estimation of energy consumption is usually based on literature instead of being calculated. In terms of the type of treatment technologies, the number of studies about LCAs of anaerobic membrane
bioreactors is limited [8, 65].

In order to figure out the environmental feasibility of AnMBRs for municipal wastewater treatment, we present a comparative LCA among full-scale AnMBRs of different configurations. This LCA differs from other LCA studies in life cycle inventory analysis, which is based on the designs of detailed full-scale reactors instead of lab-scale reactors.


Anaerobic membrane bioreactors (AnMBRs) of seven different combinations of reactor type and membrane configuration (shown in Table 3.1) are analyzed in this study, and life cycle assessment (LCA) is performed on each AnMBR.

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<td>Submerged</td>
</tr>
<tr>
<td>CSTR + GAC</td>
<td>Submerged</td>
</tr>
<tr>
<td>CSTR</td>
<td>Cross-flow</td>
</tr>
<tr>
<td>CSTR + GAC</td>
<td>Cross-flow</td>
</tr>
<tr>
<td>Anaerobic Filter</td>
<td>Cross-flow</td>
</tr>
<tr>
<td>Anaerobic Filter + GAC</td>
<td>Cross-flow</td>
</tr>
<tr>
<td>Anaerobic Filter + Aerobic Filter</td>
<td>Cross-flow</td>
</tr>
</tbody>
</table>

3.1 Design Steps of Anaerobic Membrane Bioreactors

The design process of AnMBRs is summarized into several steps, which are shown in the design roadmap shown in Figure 3.1. These steps include choosing an anaerobic reactor type, choosing a membrane configuration/type/material, designing an operation mode, designing physical and chemical cleaning, and designing methane processing. The focus of this study is decision A, B, C, D, and F (shown in bold in Figure 3.1).
Figure 3.1: Design Roadmap of Full-scale AnMBRs for Municipal Wastewater Treatment
3.1.1 Reactor Type

Continuous stirred-tank reactor (CSTR)

CSTR is commonly used as the reactor in AnMBRs. When a CSTR is paired with submerged membrane modules, the design of CSTR is shown in Figure 3.2. Influent wastewater first enters a concrete channel called influent distribution channel, and then is distributed into multiple membrane trains (Each membrane train is a concrete channel perpendicular to the influent distribution channel with a row of membrane modules submerged in it). A wet well is used to collect mixed liquor, which is recirculated back to the influent distribution channel.

![Figure 3.2: Submerged AnMBR with CSTR Reactors](image)

The width of each train \( (W_{\text{train}}) \) is assumed to be 20 ft, and the depth of each train \( (D_{\text{train}}) \) is assumed to be 12 ft. The length of CSTR or train \( (L_{CSTR}) \) is estimated based on the number of membrane cassettes \( (n_{\text{cassette}}) \) in each train (Eq.3.1), and the number of cassettes in each train is determined by the design flow rate \( (Q) \) and membrane flux \( (J) \).

\[
L_{CSTR} = \frac{5}{3} + (3 + \frac{4}{12})n_{\text{cassette}}
\]  

(3.1)
When a CSTR is paired with external cross-flow membrane modules, the length of reactor ($L_{CSTR}$) is determined by hydraulic retention time ($HRT$) shown in Eq. 3.2, where $N_{\text{train}}$ is the number of trains.

$$L_{CSTR} = \frac{Q \times HRT}{N_{\text{train}} \times W_{\text{train}} \times D_{\text{train}}} \quad (3.2)$$

Up-flow Anaerobic Filter (AF)

Anaerobic filter is another type of reactor used in AnMBRs (see Figure 3.3). It is an up-flow anaerobic bioreactor filled with packing media that allows the growth of both attached and suspended biomass. The packing media used in AF typically has a void volume of 90% to 95% [66]. Influent and recirculated flow are distributed at the bottom of the AF and flow upward through the packing media, and effluent exists at the top the AF. Biogas is collected from the cone-shape top of the AF for energy recovery.

![Figure 3.3: Anaerobic Filter](image)

The volume of the packing media required for anaerobic filters ($V_{m,\text{AF}}$) is determined by Eq. 3.3, where $Q$ is the influent flow rate, $OLR_{\text{AF}}$ is the organic loading rate of anaerobic filter, $S_{so}$ is the influent readily biodegradable substrate concentration, $X_{so}$ is the influent slowly biodegradable substrate concentration, and $N_{\text{AF}}$ is the number of anaerobic filters.
The organic loading rate for AF is about 5 to 15 \( \frac{kg-COD}{m^3-day} \) [66].

\[
V_{m, AF} = \frac{Q(S_{so} + X_{so})}{N_{AF} \times OLR_{AF}} \tag{3.3}
\]

The cross-sectional area of an AF \((A_{AF})\) is determined by Eq.3.4, where \( \alpha \) is the recirculation ratio of the AF, and \( HLR_{AF} \) is the hydraulic loading rate of anaerobic filter. The hydraulic loading rate for AF is about 10 to 20 \( m/day \) [66]. Each filter is assumed to have a maximum diameter of 40 feet (12 m), above which the number of filters \((N_{AF})\) needs to be increased.

\[
A_{AF} = \frac{Q(1 + \alpha)}{N_{AF} \times HLR_{AF}} \tag{3.4}
\]

So, the depth of the AF \((D_{AF})\) can be calculated by Eq.3.5. Filter depth is assumed to be 20 feet (6 m) maximum, above which the recirculation ratio needs to be increased.

\[
D_{AF} = \frac{V_{m, AF}}{A_{AF}} \tag{3.5}
\]

Down-flow aerobic sponge filter

When an AF is chosen as the anaerobic reactor, it can pair with a down-flow aerobic sponge polishing filter (see Fig.3.4).

The volume of packing media required for aerobic filters \((V_{m, AER})\) is determined by Eq.3.6, where \( Q \) is the influent flow rate, \( OLR_{AER} \) is the organic loading rate of aerobic filter, \( S_s \) is the influent readily biodegradable substrate concentration, \( X_s \) is the influent slowly biodegradable substrate concentration, and \( N_{AER} \) is the number of aerobic filters.

\[
V_{m, AER} = \frac{Q(S_s + X_s)}{N_{AER} \times OLR_{AER}} \tag{3.6}
\]

The cross-sectional area of aerobic filter \((A_{AER})\) is determined by Eq.3.7, where \( HLR_{AER} \) is the hydraulic loading rate of aerobic filter. Each filter is assumed to have a maximum
diameter of 40 feet (12 m), above which the number of filters ($N_{AER}$) needs to be increased.

$$A_{AER} = \frac{Q}{N_{AER} \times HLR_{AER}}$$  \hspace{1cm} (3.7)

So, the depth of the aerobic filter ($D_{AER}$) is calculated by Eq.3.8. The filter depth is assumed to be 20 feet (6 m) maximum.

$$D_{AER} = \frac{V_{m,AER}}{A_{AER}}$$  \hspace{1cm} (3.8)

Granular Activated Carbon

Granular activated carbon (GAC) can be added into either CSTR or AF. The dose of GAC is determined by a user specified GAC concentration ($C_{GAC}$) and the volume of the anaerobic reactor ($V_{reactor}$) by Eq.3.9.

$$M_{GAC} = C_{GAC} \times V_{reactor}$$  \hspace{1cm} (3.9)
3.1.2 Configuration

The configuration of AnMBRs can be either submerged or cross-flow. Submerged AnMBRs have membrane modules submerged in the anaerobic reactor, whereas cross-flow AnMBRs have membrane modules placed outside of the anaerobic reactor.

3.1.3 Membrane Type

There are three major types of membrane modules used in AnMBRs: hollow fiber, flat sheet, and multi-tube.

Hollow fiber membranes are typically used in submerged AnMBRs. An example of hollow fiber membrane is GE ZeeWeed* 500D, which is assumed to be the default hollow fiber membrane modules in this study.

Flat sheet membranes can be used either in submerged and cross-flow AnMBRs. An example of flat sheet membranes is Kubota RM515 modudles, which is assumed to be the default flat sheet membrane modules in this study.

Multi-tube membranes are typically used in cross-flow AnMBRs. An example of multi-tube membran is Pentair X-flow modules, which is assumed to be the default multi-tube membrane modules in this study.

Either type of the above-mentioned membrane modules has a nominal membrane surface area per module ($A_{\text{module}}$). The total number of membrane modules required ($N_{\text{module}}$) can be calculated by Eq.3.10. Either type of membrane modules are assumed to be replace every 7 years.

$$N_{\text{module}} = \frac{A_{\text{membrane, tot}}}{A_{\text{module}}}$$  \hspace{1cm} (3.10)

3.1.4 Membrane Material

Commercialized membrane modules are typically made of one of the following material: polyethersulfone (PES), polyethylene terephthalate (PET), polyvinylidene fluoride (PVDF), polysulfone (PS), and polytetrafluoroethylene (PTFE).
3.1.5 Operation Mode

AnMBR is usually operated at filtration-relaxation-backwashing mode. Backwashing helps remove membrane foulants to prevent filtration resistance from increasing.

Backwashing is operated according to the following description. If the entire AnMBR system requires a backwashing time \( T_{bw} \) hour/day, the system then should be divided into \( \frac{24}{T_{bw}} \) backwashing units. Backwashing is operated unit by unit, which means for a given backwashing time \( T_{bw} \), only one unit is backwashed and the rest of the units \( \left( \frac{24}{T_{bw}} - 1 \right) \) are still producing effluent (in filtration mode). If the backwashing unit backwashes at a flow rate \( Q_{bw} \), then the filtration units \( \left( \frac{24}{T_{bw}} - 1 \right) \) units need to produce a flow rate \( Q + Q_{bw} \) to maintain a net effluent flow rate \( Q \).

As a result, if the AnMBR needs to produce a filtration flux \( J \), the total membrane surface area required \( (A_{membrane, tot}) \) is calculated by Eq.3.11, where the backwashing flow rate \( Q_{bw} \) is estimated by Eq.3.12.

\[
A_{membrane, tot} = \frac{Q + Q_{bw}}{J} \quad (3.11)
\]

\[
Q_{bw} = \frac{Q \times T_{bw}}{24} \quad (3.12)
\]

An example would be 30 seconds of backwashing every half-hour filtration, leading to a total backwashing time of 0.4 hour/day.

3.1.6 Physical Cleaning

Physical cleaning applied to AnMBRs is for membrane foulants removal. For submerged AnMBRs, gas sparging is commonly used for physical cleaning. The amount biogas required \( (Q_{gas}) \) for sparging can be calculated in Eq., where SGD is the specific gas demand (volume of gas required per membrane area).

\[
Q_{gas} = SGD \times A_{membrane, tot} \quad (3.13)
\]

However, when there is activated carbon present in a submerged AnMBR, gas sparging is
not required.

For cross-flow AnMBRs, gas sparging is also not necessary because a high cross-flow velocity \( V_{x-flow} \) is always maintained in order to both apply pressure for filtration and at the same time remove membrane foulants. Retentate flow rate \( Q_R \) is calculated based on the cross-flow velocity requirement (see Eq. 3.14).

\[
Q_R = V_{x-flow} \times A_{x-section}
\]  

\( (3.14) \)

3.1.7 Chemical Cleaning

Aside from physical cleaning, chemicals are often used for membrane cleaning. Commonly used chemicals include acids, bases, and oxidants. In this study, we assume that citric acid and sodium hypochlorite (\( \text{NaOCl} \)) are used, where citric acid is for inorganic foulants removal and sodium hypochlorite is for organic foulants removal. Both cleaning-in-place (CIP or maintenance cleaning) and cleaning-out-of-place (COP) are conducted.

In the LCA, we assume an annual \( \text{NaOCl} \) consumption of \( 220 \ \text{gal} \ \text{yr}^{-1} \text{mgd}^{-1} \), with a concentration of 12.5% by weight. For citric acid, we assume an annual consumption of \( 600 \ \text{gal} \ \text{yr}^{-1} \text{mgd}^{-1} \), with a concentration of 100% (Tony Greiner, personal communication, July 11, 2014). Chemical consumptions include both CIP and COP. Chemical solutions are assumed to be stored in plastic containers that can hold the amount of solutions of a month. For chemical pumping, one pump is assumed to be used for the dosage of each type of chemical.

3.1.8 Methane Processing

The biogas produced during the anaerobic process is collected and reused for energy and heat generation. A combined heat and power system (CHP) is assumed to be used on-site. A microturbine is assumed to be used for the CHP system, which leads to a power efficiency of about 27%, and a heat efficiency of about 35% ([67]). Methane production rate \( Q_{CH_4} \) is estimated based on an assumed value of the volume of methane produced per COD removed \( (Q_{CH_4, per, COD}) \) and an assumption of COD removal shown in Eq. 3.15 and Eq.3.16, where
COD_{inf} is the influent COD concentration, COD_{eff} is the effluent concentration, and Q is the influent flow rate.

\[ Q_{CH4} = Q_{CH4, per, COD} \times M_{COD, removed} \] (3.15)

\[ M_{COD, removed} = (COD_{inf} - COD_{eff})Q \] (3.16)

3.2 Energy Consumption

Pumping

One of the main sources of energy consumption is pumping. For example, for submerged AnMBRs, there are permeate pumping, and internal recirculation pumping. For cross-flow AnMBRs, there are permeate pumping, internal recirculation pumping, and retentate pumping.

The method for energy consumption estimation is the same for either type of pumping. First, the total dynamic head (TDH) of the target system needs to be determined. Total dynamic head is composed of total static head \( H_{ts} \), friction loss \( H_f \), and minor losses \( H_m \). TDH can be calculated by Eq.3.17.

\[ TDH = H_{ts} + H_f + H_m \] (3.17)

\( H_{ts} \) is total static head and is calculated by Eq.3.18, where \( H_{ss} \) is suction static head and \( H_{ds} \) is discharge static head. Suction static head is the elevation difference between the operating water level on the suction side and the centerline of the pump. Discharge static head is the elevation difference between the centerline of the pump and the operating water level on the discharge side. Figure 3.5 illustrate \( H_{ss} \) and \( H_{ds} \) in the example of permeate pumping.

\[ H_{ts} = H_{ds} - H_{ss} \] (3.18)
Friction loss ($H_f$) refers to the head loss occurred due to the friction in pipes. $H_f$ can be estimated using Hazen-Williams equation shown in Eq.3.19, where $L$ is the length of pipes, $V$ is the velocity of water in pipes, $C$ is the Hazen-Williams coefficient (100 for 20-year pipes and 140 for new pipes), and $D$ is the diameter of pipes. Friction loss in the pipes at both suction and discharge sides of pumps needs to be considered.

$$H_f = 3.02LV^{1.85}C^{-1.85}D^{-1.17}$$ (3.19)

Minor losses ($H_m$) refer to the head losses caused by transitions (e.g. exits, entrances) and fittings (e.g. 90-degree bends, tees), and can be calculated using Eq.3.20, where $K$ is the minor loss coefficient.

$$H_m = \sum (KV^2/2g)$$ (3.20)

After TDH has been determined, the next step is to calculate brake horsepower ($BHP$), which is the horsepower required to drive a pump and can be calculated by Eq.3.21, where $Q$ (gpm) is the flow rate of pumping, $TDH(ft)$ is total dynamic head of the system, and
\( \eta_{pump} \) is the pump efficiency (assume 80\% for this study).

\[
BHP_{pump} = \frac{Q \times TDH}{3960 \times \eta_{pump}}
\]  

(3.21)

Finally, the amount of energy consumption can be calculated by Eq.3.22, where \( \eta_{motor} \) is the motor efficiency (assume 70\% for this study).

\[
E_{input} = \frac{BHP \times 0.746}{\eta_{motor}}
\]  

(3.22)

All the water pipes are sized based on water flow rate (\( Q_{water} \)) and an assumed water velocity (3-5 ft/sec). Required inner diameter of water pipe is calculated by Eq.3.23, and pipes are chosen based on inner diameter calculated and ANSI Pipe Schedule Chart in Table A.1. Water pipe is also assumed to be stainless steel.

\[
Dia_{water\ pipe\ (required)} = \sqrt{\frac{4Q_{water}}{\pi V_{water}}}
\]  

(3.23)

Gas Sparging

The brake horse power of blowers for gas sparging can be calculated by Eq.3.24, where \( Q_{gas} \) (ft\(^3\)/min) is gas flow rate, \( P \) (psig) is the blower discharge pressure, and \( \eta_{mechanical} \) is mechanical efficiency.

\[
BHP_{blower} = \frac{0.23Q_{gas} \left[ \left( \frac{14.7 + P}{14.7} \right)^{0.283} - 1.0 \right]}{\eta_{mechanical}}
\]  

(3.24)

The equation used for the energy consumption of gas sparging is the same as the one used for pumping (Eq.3.22).

The gas supply manifold and gas headers are used for conveying biogas for gas sparging. Biogas is first blown from blowers into the gas supply manifold, and then distributed into gas headers in each membrane train. Gas pipes are sized based on gas flow rate and an assumed gas velocity (3000-4000 ft/min). The required inner diameter for pipes is calculated by Eq.3.25, and pipes are chosen based on the inner diameter calculated and the ANSI Pipe
Schedule Chart shown in Table A.1. Gas pipes are all assumed to be stainless steel.

\[
\text{Di}_{\text{a, gas pipe (required)}} = \sqrt{\frac{4Q_{\text{gas}}}{\pi V_{\text{gas}}}}
\]  

(3.25)

3.3 Life Cycle Assessment

Life cycle assessment (LCA) is a methodology to assess environmental impacts associated with a product or process throughout its life cycle (from raw material extraction to final disposal). According to ISO 14040:2006, LCA has four phases, the relationships among which are iterative and is shown in Figure 3.6.

Figure 3.6: LCA relationship among different phases (Jeremy Guest, personal communication, July 11, 2014)

3.3.1 Goal and Scope

The goal of this study is to compare full-scale AnMBRs of different configurations and identify the optimal designs and operational conditions of AnMBRs resulting in minimal environmental impacts.
The functional unit in this study was defined as the treatment of 1 cubic meter of a defined primary effluent (assuming COD of about 400 mg/L) to a standard discharge quality (assuming COD of about 30 mg/L) over 30 years.

System boundary of AnMBRs is shown in Figure 3.7. Both construction and operation phase are included in the system boundary, whereas demolition phase is not included. Only first order environmental impacts (direct emissions from WWTP) and second order environmental impacts (emissions from upstream electricity and material production) are included in the system boundary ([24]). Besides, avoided impacts due to energy offset via biogas recovery is also included in the system boundary.

Figure 3.7: System Boundary of LCA for AnMBRs
3.3.2 Life Cycle Inventory Analysis

As the second phase of LCA, life cycle inventory (LCI) analysis involves quantifying an inventory of raw material, energy, and emissions entering and leaving the defined system boundary.

In this study, life cycle inventory includes both foreground and background data, and foreground data was the focus of this study. Foreground data here refers to the specific data that are required to build and operate the reactors [69]. Background data refers to more genetic material or transportation information, which in this case is less important. As defined in the system boundary, LCIs of both construction and operation phase are considered.

For construction phase, foreground inventories include the concrete needed to build reactors and pump/blower buildings, volume of excavation, piping material (assume stainless steel), and material of membrane modules, and a combined heat and power system. For excavation, a slope of 1.5 (horizontal/vertical) and a freedboard of 3 feet are assumed. Background inventories included transport by lorry, transport by rail, electricity, reinforcing steel, tap water, aluminum, limestone, chromium steel, glass, copper, synthetic rubber, rock wool, organic/inorganic chemicals, bitumen, and low-density polyethylene (LDPE), and high-density polyethylene (HDPE).

For operation phase, foreground inventories include electricity consumption and offset, chemical consumption for membrane cleaning (citric acid and NaOCl), granular activated carbon replacement, membrane replacement, and landfilling.

Direction emissions considered in this study include water emission and air emissions. Water emissions include COD, NH3, NH4+, organic nitrogen, phosphorus, and PO4−; air emissions include CH4 and CO2.

3.3.3 Life Cycle Impact Assessment

Life cycle impact assessment is to evaluate the environmental impacts based on the LCI results generated in the previous phase.

The method used for impact assessment is called "The Tool for Reduction & Assess-
ment of Chemical & Other Environmental Impacts” (TRACI), which characterizes 9 impact
categories including ozone depletion, global warming, smog pollution, acidification, eutroph-
ication, carcinogens, non-carcinogens, respiratory, ecotoxicity.

To utilize TRACI, LCIs needs to be converted into unit processes, which is accessed via
Ecoinvent v2.0 database. Unit processes are the smallest elements of life cycle inventory
data. There are several assumptions made in unit processes. First, electricity was assumed
to be generated from different sources, where 2.8% was from natural gas power plant, 46.5%
was from hard coal at power plant, 0.1% was from hydro-power power plant, 0.1% was from
oil power plant, 47.8% was from nuclear power plant, and 2.6% was from wind power plant
(The electricity source assumption is based on the state of Illinois).

3.3.4 Interpretation

Interpretation is the final phase of LCA, where life cycle environmental impact results are
evaluated. Both sensitivity and uncertainty analyses are performed for interpretation. Iter-
ative procedures are utilized for both analyses.

In sensitivity analyses, the effects of the decision variables on the environmental impacts
are evaluated. Each decision variable is assigned a range of values, and LCAs are performed
across a multidimensional decision variable space.

In uncertainty analyses, the effects of uncertainty parameters in designs of AnMBRs are
evaluated. Latin hypercube sampling are used to generate a collection of uncertainty pa-
rameters of a certain distribution, which is used to perform iterative uncertainty analyses.

3.4 MATLAB Automation

The LCAs of AnMBRs are automated using MATLAB. Important MATLAB functions and
scripts utilized in this study are summarized as follows (see Table 3.2 and Appendix B for
details).

Function “LCI_anMBR” (see Listing B.1) is used to generate life cycle inventories for
AnMBRs of user-specified configurations. The inputs include design identifiers (e.g. step A,
step B, etc), decision variables, and uncertainty parameters. The outputs include life cycle inventories from both the construction and operational phase, direction emissions, energy consumption and offset. Multiple design functions are called in the function “LCI_anMBR”, and they are focused on different design aspects of AnMBRs (see Table 3.2).

Function “Impact_Assessment” (see Listing B.2) is used to convert life cycle inventories to life cycle environmental impacts. The inputs include construction and operational inventories, direction emissions, electricity offset, and volume of wastewater treated over 30 years. The outputs include environmental impacts from both construction and operational phases, impacts from direction emissions, and impacts avoided due to energy recovery.
Table 3.2: Summary of MATLAB Scripts and Functions (Full scripts and functions can be found in Appendix B)

<table>
<thead>
<tr>
<th>Function Name</th>
<th>Listing No.</th>
<th>Function Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCI_anMBR</td>
<td>Listing B.1</td>
<td>Execute all the functions; generate data and plots</td>
</tr>
<tr>
<td>Impact_Assessment</td>
<td>Listing B.2</td>
<td>Convert life cycle inventories to life cycle environmental impacts</td>
</tr>
<tr>
<td>Execution_Script</td>
<td>Listing B.3</td>
<td>Generate life cycle inventories for AnMBRs</td>
</tr>
<tr>
<td>CSTR</td>
<td>Listing B.4</td>
<td>Design a CSTR</td>
</tr>
<tr>
<td>ANA_Filter</td>
<td>Listing B.5</td>
<td>Design a anaerobic filter</td>
</tr>
<tr>
<td>AER_Filter</td>
<td>Listing B.6</td>
<td>Design an aerobic polishing filter</td>
</tr>
<tr>
<td>Multi_Tube</td>
<td>Listing B.7</td>
<td>Design multi-tube membrane modules</td>
</tr>
<tr>
<td>Flat_Sheet</td>
<td>Listing B.8</td>
<td>Design flat sheet membrane modules</td>
</tr>
<tr>
<td>Hollow_Fiber</td>
<td>Listing B.9</td>
<td>Design hollow fiber membrane modules</td>
</tr>
<tr>
<td>Permeate_Pumping_Submerged</td>
<td>Listing B.10</td>
<td>Design permeate pumping for submerged AnMBRs</td>
</tr>
<tr>
<td>Permeate_Pumping_Cross_Flow</td>
<td>Listing B.11</td>
<td>Design permeate pumping for cross-flow AnMBRs</td>
</tr>
<tr>
<td>Gas_Sparging_Submerged</td>
<td>Listing B.12</td>
<td>Design gas sparging for submerged AnMBRs</td>
</tr>
<tr>
<td>Chemical_Cleaning</td>
<td>Listing B.13</td>
<td>Design chemical dosage for AnMBRs</td>
</tr>
<tr>
<td>Chemical_Pumping</td>
<td>Listing B.14</td>
<td>Design chemical pumping for AnMBRs</td>
</tr>
</tbody>
</table>
CHAPTER 4
RESULTS AND DISCUSSION

4.1 Impact Sources of Fixed Designs

The environmental impacts of five fixed designs (System 1 - 5) are analyzed. The results shown below (Figure 4.1 to 4.5) are based on an influent wastewater flow rate of 20 million gallons per day (MGD) over 30 years. Results are normalized to 1 m$^3$ wastewater treated. The design and operational assumptions for all five systems are summarized in Table 4.1, where HRT is the hydraulic retention time; SGD is the specific gas demand for gas sparging; TMP is transmembrane pressure; $J$ is permeate flux; $\alpha$ is internal recirculation ratio for the anaerobic reactor; $OL_{AF}$ is the organic loading rate for the anaerobic filter; $HL_{AF}$ is the hydraulic loading rate for the anaerobic filter, $OL_{AER}$ is the organic loading rate for the aerobic polishing filter; $HL_{AER}$ is the hydraulic loading rate for the aerobic polishing filter.

For System 1, gas sparging is the biggest contributor to every impact category except for eutrophication (Figure 4.1). This is because gas sparging is very energy-intensive, and thus lead to greater environmental impacts. However, eutrophication is much more sensitive to the emission of phosphorus and nitrogen than any other impact source, which explains why eutrophication is dominated by direct effluent emissions. Also, impact categories including carcinogen, non-carcinogen, respiratory, and eco-toxicity are more sensitive to steel than other contributors, and the main source of steel consumption is piping. Thus, in order to reduce the environmental impacts of these categories, a substitute material for steel could be used for piping. System 1 is far from achieving energy-positive treatment because the energy offset is insignificant compared to its high energy consumption, mostly stemming from gas sparging.

The elimination of gas sparging in System 2 causes permeate pumping to become the
Table 4.1: Design and Operational Decisions for System 1 - 5

<table>
<thead>
<tr>
<th></th>
<th>System 1</th>
<th>System 2</th>
<th>System 3</th>
<th>System 4</th>
<th>System 5</th>
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<tbody>
<tr>
<td>Reactor Type</td>
<td>CSTR</td>
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<td>AF</td>
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<tr>
<td>Addition</td>
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<td>GAC</td>
<td>-</td>
<td>-</td>
<td>AER</td>
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<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>SGD [m³ gas / m² area - hr]</td>
<td>0.23</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>OLF [kg COD / m³ day]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>HLF [m / hr]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>OLF [kg COD / m³ - day]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>HLF [m / hr]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>J [m² L / m² - hr]</td>
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<td>8.5</td>
<td>8.5</td>
<td>8.5</td>
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<td>TMP [psi]</td>
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<td>20</td>
<td>25</td>
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<td>20</td>
</tr>
<tr>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
biggest contributor to environmental impacts (Figure 4.2). Recirculation pumping is less significant as a impact contributor compared to permeate pumping because of the low recirculation ratio and pressure head assumed for this system, and its environmental impacts will increase as the recirculation ratio and pressure head increases. The electricity demand from pumping is still a fraction of that which was required by gas sparging, making energy-positive/neutral treatment possible through the addition of GAC for membrane scouring.

System 3 adopts a cross-flow configuration, so retentate pumping is required. Permeate pumping is still the biggest contributor to environmental impacts (Figure 4.3). However, the impacts caused by retentate pumping will increase as cross-flow velocity increases. Although gas sparging is not needed for this system, it is still unlikely to achieve energy-positive/neutral treatment due to the high energy consumption by both permeate and retentate pumping, it is still unlikely to achieve energy-positive/neutral.

In System 4, lift pumping is an additional source of environmental impacts compared to the previous three systems because instead of using a CSTR as the anaerobic reactor, an up-flow anaerobic filter is utilized, which requires lift pumping of the influent. Nevertheless, lift pumping still consumes less energy than permeate pumping due to a lower pressure head differential and thus causes less environmental impact (Figure 4.4). However, the building of anaerobic filter and cross-flow configuration requires more piping material, which leads to greater impacts in the categories of carcinogen, non-carcinogen, respiratory, and eco-toxicity.

System 5 is very similar to System 4 except for the addition of the aerobic polishing filter, which reduces the COD concentration of the wastewater entering the cross-flow membrane module. As a result, a lower TMP is required to produce the same permeate flux. However, the aerobic filter also causes a static head loss in the system, which has the opposite effect to the reduction in TMP in terms of the energy consumption of permeate pumping. Figure 4.5 shows that the energy consumption of permeate pumping decreases compared to System 4, which means the addition of an aerobic filter could reduce the overall energy consumption, but not enough to make System 5 energy-positive/neutral.
Figure 4.1: Environmental Impact Sources of System 1

Figure 4.2: Environmental Impact Sources of System 2
Figure 4.3: Environmental Impact Sources of System 3

Figure 4.4: Environmental Impact Sources of System 4
4.2 Relative Environmental Performance of Configurations

4.2.1 Comparison of Total Environmental Impacts

System 1 has higher environmental impacts in the impact category of ozone depletion, global warming, smog, and acidification because these impact categories are more sensitive to energy consumption (Figure 4.6). The impact of eutrophication is almost the same for every system because eutrophication is dominated by nitrogen and phosphorus in the effluent, which are assumed to be the same for every system. Avoided impacts from energy offsets are also the same across all systems because the same methane production and treatment efficacy was assumed. System 4 has slightly lower impacts in every category than System 5, but both of them cause much higher impacts in carcinogenics and eco-toxicity than the other systems. System 2 has the lowest environmental impacts for every impact category, making it the most environmentally-sustainable configuration of the five.
4.2.2 Comparison of Impacts from Construction Phase

System 1 has lower environmental impacts stemming from construction than any other system in six of nine impact categories because it requires less consumption of construction material (Figure 4.7). The only difference in construction materials between System 1 and System 2 is the addition of GAC, causing System 2 to have higher impacts in carcinogen, non-carcinogen, and eco-toxicity than System 1. As a result, the environmental impacts of GAC cannot be neglected. Figure 4.7 also shows that AnMBRs of a cross-flow configuration tend to have higher environmental impacts from construction those of a submerged configuration.
4.2.3 Comparison of Impacts from Operational Phase

In contrast to the construction phase, System 1 has the highest environmental impacts from the operational phase (Figure 4.8). Given that System 2 has the lowest operational environmental impacts among the five systems, it is clear that submerged configurations are not inherently bad, but rather the elimination of gas sparging is very important in lowering environmental impacts from the operational phase. Despite differences in reactor type (Decision A) and inclusion/exclusion of an aerobic polishing filter, System 3, System 4, and System 5 are very close in their impacts. This similarity stems from consistent electricity demands from permeate and (when applicable) lift pumping.
4.3 Sensitivity Analysis of Design Decisions

The sensitivity of three design decisions of AnMBR systems (including reactor type, configuration, and membrane type) have been evaluated, and the design decisions are shown in Table 4.2. A box-and-whisker plot (shown in Figure 3.1) is utilized to reflect the influence of these design decisions on the environmental impacts (demonstrated as global warming potential), where the minimum, maximum, 25%, 50%, and 75% values are denoted in the figure. The global warming potential shown in the figure is normalized to 1 $m^3$ of wastewater treated.

The first design decision evaluated is the choice of reactor type. According to the design roadmap (Figure 3.1), the reactor type for AnMBRs can be either CSTR or anaerobic filter (AF). Granular activated carbon (GAC) and aerobic polishing filter (AER) can be added based on the reactor chosen, where GAC can be added to both CSTR and AF while AER can be only paired with AF. The choice of CSTR results in a slightly wider 25% to 75% range of global warming potential than AF does (Figure 4.9). The higher end of the range
is probably caused by submerged AnMBRs with a CSTR, and the lower end of the range caused by submerged AnMBRs with a CSTR and also the addition of GAC.

The second design decision evaluated is the choice of AnMBR configuration, which include submerged and cross-flow AnMBRs. Submerged configuration results in a slightly wider 25% to 75% range of global warming potential than the cross-flow configuration does while the submerged configuration has a much higher median than the cross-flow configuration (Figure 4.9). The reason of the wider 25% to 75% range resulted by submerged AnMBRs is the same as explained for the first design decision.

The third design decision evaluated is the choice of membrane type, including hollow fiber (HF), flat sheet (FS), and multi-tube (MT). Flat sheet membrane results in the widest 25% to 75% range of global warming potential while hollow fiber membrane does the opposite (Figure 4.9). This is because flat-sheet membranes are used in both submerged and cross-flow configuration, while multi-tube and submerged membrane is exclusively used in the cross-flow and submerged configuration respectively.

![Figure 4.9: Sensitivity Analysis of Design Decisions](image-url)
Table 4.2: AnMBR Systems Evaluated for Sensitivity Analysis

<table>
<thead>
<tr>
<th>A - REACTOR TYPE</th>
<th>A1 - ADDITION</th>
<th>B - CONFIGURATION</th>
<th>C - MEMBRANE TYPE</th>
<th>D - MEMBRANE MATERIAL</th>
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<td>HF</td>
<td>PET</td>
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<tr>
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<td>HF</td>
<td>PTFE</td>
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<td>FS</td>
<td>PET</td>
</tr>
<tr>
<td>CSTR</td>
<td>none</td>
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<td>FS</td>
<td>PTFE</td>
</tr>
<tr>
<td>CSTR</td>
<td>+GAC</td>
<td>Submerged</td>
<td>HF</td>
<td>PET</td>
</tr>
<tr>
<td>CSTR</td>
<td>+GAC</td>
<td>Submerged</td>
<td>HF</td>
<td>PTFE</td>
</tr>
<tr>
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</tr>
<tr>
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<td>PTFE</td>
</tr>
<tr>
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</tr>
<tr>
<td>AF</td>
<td>+GAC</td>
<td>Cross-flow</td>
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<td>Cross-flow</td>
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<td>AF</td>
<td>+AER</td>
<td>Cross-flow</td>
<td>FS</td>
<td>PTFE</td>
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</table>
The LCA results demonstrate that AnMBRs designed as a continuous stirred-tank reactor (CSTR) with a submerged membrane configuration are likely to be the most energy-intensive and also the least environmentally-sustainable. This is because gas sparging is required for this configuration and it is extremely energy-intensive, which is likely to eliminate the possibility of any AnMBR becoming an energy-positive/neutral system.

Nevertheless, the addition of granular activated carbon into the AnMBR of the submerged configuration would circumvent the principal source of life cycle impacts (gas sparging) and achieve the most environmental sustainable design. However, the case where GAC is added into AnMBRs of the cross-flow configuration is not included in this study, and will be worth a comparison to the case where GAC is added into AnMBRs of the submerged configuration.

No matter which AnMBR system is considered, environmental impacts from the construction phase are always dwarfed by those from the operational phase, where the energy consumption is the biggest contributor the environmental impacts.

AnMBRs of the cross-flow configuration, in general, are less energy-intensive and thus cause lesser environmental impacts than AnMBRs of the submerged configuration which often rely on gas sparging to mitigate fouling. Also, AnMBRs with the anaerobic filter are more likely to cause more environmental impacts from the construction phase than AnMBRs with the CSTR are due to a higher consumption of concrete, steel and other construction materials.

Furthermore, the benefit (the reduction in the transmembrane pressure of permeate filtration causing a lower energy consumption of permeate pumping) of adding the aerobic polishing filter after the anaerobic filter is likely to be offset by the static head loss caused by it. Unless the addition of the aerobic filter could reduce the transmembrane pressure by
more than its resulting static head loss, while maintaining the same permeate flux, it is not recommended as a means to reduce life cycle environmental impacts of AnMBR.

In addition, eutrophication is much more sensitive to the emissions of effluent wastewater than any other impact contributor. Also, impact categories including carcinogen, non-carcinogen, respiratory, and eco-toxicity are more sensitive to the consumption of construction material, especially stainless steel, while ozone depletion, global warming, smog, and acidification are more sensitive to energy consumption.

Finally, the design decisions of AnMBRs included in this study are limited, and further research is encouraged to focus on the influence of the other design decisions that are listed in the AnMBR design roadmap on environmental impacts.
AnMBRs, as an anaerobic technology, is becoming popular for municipal wastewater treatment due to the paradigm shift of WWTP designs from aerobic-based to anaerobic-based technologies.

The first significance of this study is that a detailed design roadmap was developed for AnMBRs because as an emerging technology, AnMBRs have not been implemented by the wastewater treatment industry and detailed design strategies still remain unclear. Thus, this roadmap can guide wastewater treatment plant designers as a blueprint for the future research development and design of AnMBR technology.

The second significance is that a quantitative LCA tool of AnMBRs was developed in this study, which helps decision makers to get a better understanding of AnMBR technology from an environmental sustainability perspective. Decisions of whether AnMBR technology should be widely adopted in the wastewater treatment industry in the future is highly dependent on whether AnMBR technology as a whole has the potential to achieve financial viable, energy-positive/neutral treatment, and also what the design and operational decisions should be made to help AnMBR technology achieve this goal. To this end, additional research is recommended focusing on elucidating the broader sustainability of AnMBR, and to advance its wastewater treatment efficacy.
CHAPTER 7
REFERENCES


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APPENDIX A

TABLES

A.1 ANSI Pipe Schedule Chart
Table A.1: ANSI Pipe Schedule Chart

<table>
<thead>
<tr>
<th>Nominal Pipe Size</th>
<th>O.D. [in]</th>
<th>Pipe Thickness [in] (10s)</th>
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<td>1/4</td>
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</table>
Listing B.1: Life Cycle Inventory Analysis

```matlab
function [INV_CON, INV_OP, DEmis, Power_pct, E_input_kWh, E_offset_kWh, ... V_treated, Output_LCC] = LCI_anMBR(step_A, step_A1, step_B, step_C, ... step_D, DVariable, UParameter)

% Input:
% step_A (Reactor type) input 'CSTR or 'AF'
% step_A1: If there's aerobic polishing filters added, input '+AER'
% If there's GAC added, input '+GAC'
% step_B (Configuration): input 'Submerged' or 'Cross-flow'
% step_C (Membrane type) input 'MT' for "multi-tube", or 'HF' for ...
% "hollow fiber", or 'FS' for "flat sheet"
% step_D (Membrane material) input 'PET' or 'PTFE'
% step_F (Physical cleaning)
% step_H (Soluble methane management)
% step_I (Methane processing)
% DVariable: A vector containing Decision variables
% UParameter: A vector containing Uncertainty parameters

% Output:
% Construction inventory matrix, INV_CON
% Operational inventory matrix, INV_OP
% Direct emission matrix, DEmis
% Energy source percentage matrix, Power_pct
% Total energy input over N years, E_input_kWh [kWh]
% Total energy offset over N years, E_offset_kWh [kWh]
% Volume of treated wastewater over N years, V_treated [m^3]
```
% Output matrix for LCC, Output_LCC

Year = 30; % Assumed years of operation

% Influent

Q_mgd = UParameter(1); % Influent volumetric flow rate [mgd]

V_treated = Q_mgd * 3785.41178 * Year * 365; % [m^3] Volume of treated wastewater over N years

S_SO = UParameter(2); % [mg-COD/L] or [g/m^3]

X_SO = UParameter(3); % [mg-COD/L] or [g/m^3]

COD_inf = S_SO + X_SO; % [mg-COD/L] or [g/m^3]

% Effluent

COD_eff = 30; % [mg-COD/L] or [g/m^3]

NH3_eff = 0; % [mg-N/L]

NH4_eff = 25; % [mg-N/L] % Hospido, 2012

Org_N_eff = 0; % [mg-N/L]

P_eff = 0; % [mg-N/L]

PO4_eff = 3; % [mg-N/L] % Hospido, 2012

CH4_eff = 0.67 * 10^-3; % [mg-CH4/L] % Hospido, 2012

CO2_eff = 127 * 10^-3; % [mg-CO2/L] % Hospido, 2012

% Assign values to decision variables

if strcmp(step_A, 'CSTR') && strcmp(step_B, 'Submerged')
    J = DVariable(1);
    TMP = DVariable(2);
    N_train = DVariable(3);
    IRR = DVariable(4);
elseif strcmp(step_A, 'CSTR') && strcmp(step_B, 'Cross-flow')
    J = DVariable(1);
    TMP = DVariable(2);
    N_train = DVariable(3);
    IRR = DVariable(4);
    HRT = DVariable(5);
elseif strcmp(step_A, 'AF') && ~strcmp(step_A1, '+AER')

55
J = DVariable(1);
TMP = DVariable(2);
OL_AF = DVariable(3);
HL_AF = DVariable(4);
R_AF = DVariable(5);

elseif strcmp(step_A, 'AF') && strcmp(step_A1, '+AER')

J = DVariable(1);
TMP = DVariable(2);
OL_AF = DVariable(3);
HL_AF = DVariable(4);
R_AF = DVariable(5);
OL_AER = DVariable(6);
HL_AER = DVariable(7);

end

%% Step A - Reactor Type
if strcmp(step_A, 'CSTR')

disp('CSTR');

if strcmp(step_B, 'Submerged')
    % Reactor size depends on # of membrane modules submerged, so
    % membrane functions are called here.
    % if strcmp(step_C, 'HF')
        [M_Membrane_kg, N_SU, N_LU_pt, A_LU] = Hollow_Fiber(Q_mgd, ...
            J, N_train, 0.4); % Call membrane function (hollow fiber)
    % elseif strcmp(step_C, 'FS')
        [M_Membrane_kg, N_SU, N_LU_pt, A_LU] = ...
            Flat_Sheet_Submerged(Q_mgd, J, N_train, 0.4); % Call ...
            membrane function (flat sheet)
    end
    [D_train, L_train, W_train, W_N_trains, W_PB, L_BB, VWC_CSTR, ...
        VSC_CSTR, VEX_CSTR] = CSTR_Submerged(Q_mgd, N_train, ...
        N_LU_pt); % Call CSTR function (submerged membrane)
elseif strcmp(step_B, 'Cross-flow')

end

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V_reactor = N_train * D_train * L_train * W_train; % [ft^3] Volume of reactor

elseif strcmp(step_A, 'AF')
    disp('Anaerobic filter');
    [V_m_AF, D_AF, Dia_AF, N_AF, VWC_AF, VSC_AF, VEX_AF] = ... 
        ANA_Filter(Q_mgd, S_SO, X_SO, OL_AF, HL_AF, R_AF); % Call anaerobic filter function
    V_reactor = N_AF * V_m_AF / 0.5; % [ft^3] Volume of reactor (assume 50% volume is occupied by packing media)
    [M_LDPE_AF_kg, M_HDPE_AF_kg] = Packing_Media (V_m_AF); % Call packing media function
    [Q_LIFT_mgd, NP_LIFT, P_input_LIFT, M_SS_LIFT] = ... 
        Lift_Pumping_Cross_Flow(Q_mgd, N_AF, D_AF); % Call lift pumping function
    [Q_IR_mgd, NP_IR, P_input_IR, M_SS_IR] = ... 
        Recirculation_Pumping_Cross_Flow(Q_mgd, R_AF, N_AF, D_AF, Dia_AF); % Call recirculation pumping function
end

%% Step A1 - Aerobic Polishing Filter/GAC
if strcmp(step_A1, '+AER')
    disp('+AER');
    [V_m_AER, D_AER, Dia_AER, N_AER, VWC_AER, VSC_AER, VEX_AER] = ... 
        AER_Filter(Q_mgd, S_SO, X_SO, OL_AER, HL_AER); % Call aerobic filter function
    [M_LDPE_AER_kg, M_HDPE_AER_kg] = Packing_Media (V_m_AER); % Call packing media function
VEL_xflow = 1; % [m/s] Lower cross-flow velocity

elseif strcmp(step_A1, '+GAC')
    disp('+GAC');

    C_GAC = 100; % [g/L] or [kg/m^3] Concentration of GAC (Yoo, 2012)
    M_GAC_kg = C_GAC * V_reactor * 0.0283168; % [kg/m^3] Mass of GAC
    VEL_xflow = 1; % [m/s] Lower cross-flow velocity

else if strcmp(step_A1, 'none')
    disp('None');
    VEL_xflow = 2; % [m/s] Higher cross-flow velocity
end

%% Step B, C, D - Membrane Configuration & Type & Material
if strcmp(step_B, 'Submerged')
    if strcmp(step_C, 'HF')
        [M_Membrane_kg, N_SU, N_LU_pt, A_LU] = Hollow_Fiber(Q_mgd, J, ...
            N_train, 0.4);
    elseif strcmp(step_C, 'FS')
        [M_Membrane_kg, N_SU, N_LU_pt, A_LU] = ...
            Flat_Sheet_Submerged(Q_mgd, J, N_train, 0.4);
    end

    [Q_PERM_mgd, NP_PERM, P_input_PERM, M_SS_PERM] = ...
        Permeate_Pumping_Submerged(Q_mgd, N_train, D_train, L_train, ...
            W_N_trains, TMP); % Call permeate pumping function

else if strcmp(step_A1, 'none')
    SGD = 0.23; % Specific gas demand [Nm^3 gas/m^2 membrane area-h] ...
        (based on Robles, 2012)
    freq = 1; % freq: Gas sparging frequency [sparging time/total time]
    [Q_gas_cfm, NB, P_input_blower, M_SS_gh, M_SS_gsm, OD_gh, OD_gsm] = ...
        Gas_Sparging_Submerged(N_train, N_LU_pt, A_LU, SGD, L_train, ...
            W_PB, L_BB, freq); % Call gas sparging function
end

elseif strcmp(step_B, 'Cross-flow')
    disp('Cross-flow');
    if strcmp(step_C, 'MT')
[M_Membrane_kg, N_SU, N_LU, Q_R_mgd] = Multi_Tube(Q_mgd, J, ...
   0.4, VEL_xflow);
[Q_PERM_mgd, NP_PERM, P_input_PERM, M_SS_PERM] = ...
   Permeate_Pumping_Cross_Flow(Q_mgd, N_LU, TMP);
elseif strcmp(step_C, 'FS')
   [M_Membrane_kg, N_SU, N_LU, Q_R_mgd] = Flat_Sheet_Xflow(Q_mgd, ...
   J, 0.4, VEL_xflow);
   [Q_PERM_mgd, NP_PERM, P_input_PERM, M_SS_PERM] = ...
   Permeate_Pumping_Cross_Flow(Q_mgd, N_LU, TMP);
end

% Call retentate pumping function
if strcmp(step_A, 'AF')
   if strcmp(step_C, 'MT')
      [NP_R, P_input_R, M_SS_R] = Retentate_Pumping_AF(Q_R_mgd, ...
         N_LU, D_AF);
   elseif strcmp(step_C, 'FS')
      [NP_R, P_input_R, M_SS_R] = Retentate_Pumping_AF(Q_R_mgd, ...
         N_LU, D_AF);
   end
elseif strcmp(step_A, 'CSTR')
   if strcmp(step_C, 'MT')
      [NP_R, P_input_R, M_SS_R] = Retentate_Pumping_CSTR(Q_R_mgd, ...
         N_LU, D_train);
   elseif strcmp(step_C, 'FS')
      [NP_R, P_input_R, M_SS_R] = Retentate_Pumping_CSTR(Q_R_mgd, ...
         N_LU, D_train);
   end
end

%% Step G - Chemicals Cleaning
[M_NaOCl_kg, Q_NaOCl_weekly, M_CA_kg, Q_CA_weekly] = Chemical_Cleaning ... 
   (Q_mgd, Year); % Call chemical cleaning function
% NaOCl Pumping
[Q_NaOCl_mgd, NP_NaOCl, P_input_NaOCl, M_SS_NaOCl, M_HDPE_NaOCl_kg] = ...
    Chemical_Pumping(Q_NaOCl_weekly); % Call chemical pumping function
%
% Citric acid Pumping
[Q_CA_mgd, NP_CA, P_input_CA, M_SS_CA, M_HDPE_CA_kg] = ...
    Chemical_Pumping(Q_CA_weekly); % Call chemical pumping function

M_HDPE_CHEM_kg = M_HDPE_NaOCl_kg + M_HDPE_CA_kg;
M_SS_CHEM = M_SS_NaOCl + M_SS_CA;

%% Step I - Methane Processing
Q_CH4_per_kg_COD = 0.2; % [m^3-CH4/kg-COD removed] Unit CH4 production rate
Q_cmd = Q_mgd * 3785.41178; % [m^3/day] Unit conversion
M_COD_removed = (COD_inf - COD_eff)/10^3 * Q_cmd; % [kg-COD/day] Daily ...
    COD removal
Q_CH4 = Q_CH4_per_kg_COD * M_COD_removed; % [m^3-CH4/day]

[P_offset] = CHP(Q_CH4); % Call combined heat and power function
E_offset_kWh = P_offset * Year * 365 * 24; % [kWh] Total electricity ...
    offset over N years

%% Sludge Handling
Q_WAS = 0.01 * Q_mgd;
[P_input_GBT, M_SS_GBT, M_COD_WAS] = Sludge_Handling (Q_CH4, Q_WAS, ...
    M_COD_removed);

%% Life Cycle Inventory Summary
%% Construction Phase
%% Concrete
if strcmp(step_A, 'CSTR')
    VSC = VSC_CSTR;
}
VWC = VWC_CSTR;
VEX = VEX_CSTR;

elseif strcmp(step_A, 'AF') && ~strcmp(step_A1, '+AER')
VSC = VSC_AF;
VWC = VWC_AF;
VEX = VEX_AF;

elseif strcmp(step_A, 'AF') && strcmp(step_A1, '+AER')
VSC = VSC_AF + VSC_AER;
VWC = VWC_AF + VSC_AER;
VEX = VEX_AF + VEX_AER;
end

VC_m3 = (VSC + VWC) * 0.0283168; % [m^3] Unit conversion from [ft^3] to ...
   [m^3]

% Excavation
VEX_m3 = VEX * 0.0283168; % [m^3] Unit conversion from [ft^3] to [m^3]

% GAC
if ~strcmp(step_A1, '+GAC')
M_GAC_kg = 0;
end

% Stainless Steel
if strcmp(step_A, 'CSTR')
M_LDPE_kg = 0;
M_HDPE_kg = M_HDPE_CHEM_kg;
if strcmp(step_B, 'Submerged') && strcmp(step_A1, 'none')
M_Steel_kg = (M_SS_PERM + M_SS_IR + M_SS_gh + M_SS_gsm + ... 
   M_SS_CHEM);
elseif strcmp(step_B, 'Submerged') && strcmp(step_A1, '+GAC')
M_Steel_kg = (M_SS_PERM + M_SS_IR + M_SS_CHEM);
elseif strcmp(step_B, 'Cross-flow')
M_Steel_kg = (M_SS_PERM + M_SS_IR + M_SS_R + M_SS_CHEM);
end

elseif strcmp(step_A, 'AF')
    if strcmp(step_A1, '+AER')
        \[M_{LDPE} kg = M_{LDPE AF} kg + M_{LDPE AER} kg;\]
        \[M_{HDPE} kg = M_{HDPE AF} kg + M_{HDPE AER} kg + M_{HDPE CHEM} kg;\]
        \[M_{Steel} kg = (M_{SS LIFT} + M_{SS IR} + M_{SS PERM} + M_{SS R} + ...\]
        \[M_{SS CHEM}); \% [kg] based on values determined above\]
        else
            \[M_{LDPE} kg = M_{LDPE AF} kg;\]
            \[M_{HDPE} kg = M_{HDPE AF} kg + M_{HDPE CHEM} kg;\]
            \[M_{Steel} kg = (M_{SS LIFT} + M_{SS IR} + M_{SS PERM} + M_{SS R} + ...\]
            \[M_{SS CHEM}); \% [kg] based on values determined above\]
        end
    end

% Call the "LCI_CON" function to generate construction inventory matrix
INV_CON = LCI_CON (VC_m3, VEX_m3, M_Steel_kg, M_Membrane_kg, M_LDPE_kg, ...
    M_HDPE_kg, M_GAC_kg, step_D);

% Operational Phase
% Total Energy Consumption
if strcmp(step_A, 'CSTR')
    if strcmp(step_A1, 'none') && strcmp(step_B, 'Submerged')
        \[P_{input tot} = P_{input PERM} + P_{input IR} + P_{input blower} + ...\]
        \[P_{input NaOCl} + P_{input CA}; \% [Kw] Total power input\]
        \[Power_pct = [P_{input PERM}/P_{input tot}, P_{input IR}/P_{input tot}, ...\]
        \[P_{input blower}/P_{input tot}, (P_{input NaOCl} + ...\]
        \[P_{input CA})/P_{input tot}];\]
    elseif strcmp(step_B, 'Cross-flow')
        \[P_{input tot} = P_{input PERM} + P_{input IR} + P_{input R} + ...\]
        \[P_{input NaOCl} + P_{input CA}; \% [Kw] Total power input\]
        \[Power_pct = [P_{input PERM}/P_{input tot}, P_{input IR}/P_{input tot}, ...\]
elseif strcmp(step_A1, '+GAC') && strcmp(step_B, 'Submerged')
  P_input_tot = P_input_PERM + P_input_IR + P_input_NaOCl + ...
  P_input_CA; % [Kw] Total power input
  Power_pct = [P_input_PERM/P_input_tot, P_input_IR/P_input_tot, ...
  (P_input_NaOCl + P_input_CA)/P_input_tot];
end
elseif strcmp(step_A, 'AF')
  if strcmp(step_B, 'Cross-flow')
    P_input_tot = P_input_PERM + P_input_LIFT + P_input_IR + ...
    P_input_R + P_input_NaOCl + P_input_CA; % [Kw] Total power ...
    input
    Power_pct = [P_input_LIFT/P_input_tot, ...
    P_input_PERM/P_input_tot, ...
    P_input_IR/P_input_tot, P_input_R/ P_input_tot, ...
    (P_input_NaOCl + P_input_CA)/P_input_tot];
  elseif strcmp(step_A1, '+GAC') && strcmp(step_B, 'Submerged')
    P_input_tot = P_input_PERM + P_input_LIFT + P_input_IR + ...
    P_input_R + P_input_NaOCl + P_input_CA; % [Kw] Total power ...
    input
    Power_pct = [P_input_LIFT/P_input_tot, P_input_IR/P_input_tot, ...
    (P_input_NaOCl + P_input_CA)/P_input_tot];
  end
end
E_input_kWh = P_input_tot * Year * 365 * 24; % [kWh] Total electricity ...
  consumption over N years
INV_OP = [0; 0; 0; M_NaOCl_kg; E_input_kWh; 0; 0; 0; M_CA_kg]; % ...
  Operational inventory matrix

%%% Direction Emissions
% Total emissions over N years
COD_water = COD_eff /10^3 * V_treated; % [kg-COD]
NH3_water = NH3_eff /10^3 * V_treated; % [kg-N/L]
NH4_water = NH4_eff /10^3 * V_treated; % [kg-N/L]
Org_N_water = Org_N_eff /10^3 * V_treated; % [kg-N/L]
P_water = P_eff /10^3 * V_treated; % [kg-N/L]
PO4_water = PO4_eff /10^3 * V_treated; % [kg-N/L]
CH4_air = CH4_eff /10^3 * V_treated; % [kg-CH4/L]
CO2_air = CO2_eff /10^3 * V_treated; % [kg-CO2/L]

DEmis = [COD_water; NH3_water; NH4_water; Org_N_water; P_water; ... 
        PO4_water; CH4_air; CO2_air];

% Output for Cost Estimation
if strcmp(step_B, 'Submerged')
    Output_cost = [VWC, VSC, VEX, Q_PERM_mgd, NP_PERM, Q_IR_mgd, NP_IR,
                   Q_gas_cfm, NB, Q_NaOCl_mgd, NP_NaOCl, Q_CA_mgd, NP_CA, N_SU];
elseif strcmp(step_B, 'Cross-flow')
    Output_cost = [VWC, VSC, VEX, Q_PERM_mgd, NP_PERM, Q_IR_mgd, NP_IR,
                   Q_NaOCl_mgd, NP_NaOCl, Q_CA_mgd, NP_CA, N_SU];
end

Listing B.2: Impact Assessment

function [IMPACT_CON, IMPACT_OP, IMPACT_DE, IMPACT_avoided] = ...
    Impact_Assessment (INV_CON, INV_OP, DEmis, E_offset_kWh, V_treated)
% Input:
% Construction Inventories, INV_CON =
% [1-Concrete; 2-Reinforcing steel; 3-Tap water; 4-Aluminum; ...
  5-Limestone;
% 6-Chromium Steel; 7-Flat glass; 8-Copper; 9-Sythetic rubber; ...
  10-Rock wool;
% 11-Bitumen; 12-LDPE; 13-HDPE; 14-Excavation; 15-Operation; ...
  16-Transport;
% 17-Extrusion; 18-Transport; 19-Electricity; 20-Organic chemicals;
% 21-Inorganic chemicals; 22-PET; 23-PTFE; 24-GAC; 25-CHP;
% Operational Inventories, INV_OP =
% [1-Acetic acid; 2-Methanol; 3-Iron; 4-Sodium hypochlorite;
% 5-Electricity; 6-Chlorine; 7-Methyl methacrylate; 8-Disposal; ...
% 9-Citric Acid]
% Direction emissions, DEmis (8x1 matrix)
% Output:
% Impacts from construction phase, IMPACT_CON (normalized to per m^3 wastewater treated)
% Impacts from operational phase, IMPACT_OP (normalized to per m^3 wastewater treated)
% Impacts from direct emissions, IMPACT_DE (normalized to per m^3 wastewater treated)
% Avoided impacts from energy offset, IMPACT_avoided (normalized to per m^3 wastewater treated)

%% Construction Phase
UP_CON = zeros(39,1); % Initialize Ecoinvent Unit Process matrix
UP_CON(1) = INV_CON(1); % Concrete, normal \{CH\} production | Alloc ...
    Def, U
UP_CON(2) = INV_CON(2); % Reinforcing steel \{RER\} production | Alloc ...
    Def, U
UP_CON(3) = INV_CON(3); % Tap water, at user/RER U
UP_CON(4) = INV_CON(4); % Aluminium, production mix, at plant/RER U

% --------------------------- Limestone ---------------------------------
UP_CON(5) = INV_CON(5); % Lime \{CH\} production, milled, loose | Alloc ...
    Def, U
UP_CON(6) = INV_CON(5); % Limestone, crushed, for mill \{CH\} production ...
    | Alloc Def, U
UP_CON(7) = INV_CON(5); % Limestone, unprocessed \{CH\} limestone quarry ...
    operation | Alloc Def, U
UP_CON(8) = INV_CON(6); % Steel, chromium steel 18/8, hot rolled {RER} | production | Alloc Def, U

UP_CON(9) = INV_CON(7); % Flat glass, uncoated {RER} | production | ...
    Alloc Def, U

% -------------------------- Copper ------------------------------
UP_CON(10) = INV_CON(8); % Copper {RER} | production, primary | Alloc ...
    Def, U

UP_CON(11) = INV_CON(8); % Copper concentrate {RER} | copper mine ...
    operation | Alloc Def, U

UP_CON(12) = INV_CON(9); % Synthetic rubber {RER} | production | Alloc ...
    Def, U

% ------------------------- Rock wool ------------------------------
UP_CON(13) = INV_CON(10); % Rock wool {CH} | production | Alloc Def, U

UP_CON(14) = INV_CON(10); % Rock wool, packed {CH} | production | Alloc ...
    Def, U

UP_CON(15) = INV_CON(11); % Bitumen, at refinery/RER U

% ------------------------ Polyethylene -----------------------------
UP_CON(16) = 0.5 * INV_CON(12); % Polyethylene, high density, granulate ...
    {RER} | production | Alloc Def, U

UP_CON(17) = 0.5 * INV_CON(13); % Polyethylene, low density, granulate ...
    {RER} | production | Alloc Def, U

UP_CON(18) = INV_CON(14); % Excavation, hydraulic digger {RER} | ...
    processing | Alloc Def, U

% ------------------------ Operation -------------------------------
UP_CON(19) = INV_CON(15); % Operation, freight train/RER U

UP_CON(20) = 0; % Operation, freight train, diesel/RER U
UP_CON(21) = INV_CON(16); % Transport, freight train {US} | diesel | ...
   Alloc Def, U
UP_CON(22) = INV_CON(17); % Extrusion, plastic pipes {RER} | production ...
   | Alloc Def, U
UP_CON(23) = INV_CON(18); % Transport, freight, lorry 16-32 metric ton, ...
   EURO5 {RER} | transport, freight, lorry 16-32 metric ton, EURO5 | ...
   Alloc Def, U

% ------------------------ Electricity ----------------------------------
% Electricity source percentages are based on the state of Illinois
UP_CON(24) = 0.028 * INV_CON(19); % Electricity, natural gas, at power ...
   plant/US U
UP_CON(25) = 0.465 * INV_CON(19); % Electricity, hard coal, at power ...
   plant/US U
UP_CON(26) = 0.001 * INV_CON(19); % Electricity, hydropower, at pumped ...
   storage power plant/US U
UP_CON(27) = 0; % Electricity, hydropower, at power plant/CH U
UP_CON(28) = 0.001 * INV_CON(19); % Electricity, high voltage {GB} | ...
   electricity production, oil | Alloc Def, U
UP_CON(29) = 0.478 * INV_CON(19); % Electricity, nuclear, at power ...
   plant/US U
UP_CON(30) = 0.026 * INV_CON(19); % Electricity, at wind power plant ...
   800kw/RER U
UP_CON(31) = 0.001 * INV_CON(19); % Electricity, high voltage {CH} | ...
   treatment of municipal solid waste, incineration | Alloc Def, U

UP_CON(32) = INV_CON(20); % Chemical, organic {GLO} | production | Alloc ...
   Def, U
UP_CON(33) = INV_CON(21); % Chemical, inorganic {GLO} | production | ...
   Alloc Def, U
UP_CON(34) = INV_CON(22); % Polyethylene terephthalate, granulate, ...
   amorphous {RER} | production | Alloc Def, U
UP_CON(35) = INV_CON(23); % Tetrafluoroethylene {RER} | production | ...
   Alloc Def, U
UP_CON(36) = INV_CON(24); % Carbon black {GLO} | production | Alloc Def, U
UP_CON(37) = INV_CON(25); % Mini CHP plant, common components for ...
heat+electricity {CH}| construction | Alloc Def, U

% TRACI characterization factors
% --> Ecoinvent 3.0 (TRACI 2.0)
CF_CON = [CF_ozo_con, CF_gwm_con, CF_smg_con, CF_acd_con, CF_eut_con, ...
    CF_car_con, CF_nca_con, CF_rsp_con, CF_ect_con]; % characterization ...
    factor matrix
UP_CON_matrix = [UP_CON, UP_CON, UP_CON, UP_CON, UP_CON, UP_CON, ...
    UP_CON, UP_CON, UP_CON]; % unit process matrix
IMPACT_CON = UP_CON_matrix .* CF_CON ./ V_treated; % Construction ...
    impact from each unit process

% Operational Phase
UP_OP = zeros(20,1); % Initialized Ecoinvent Unit Process matrix
% ------------------ Acetic acid (pick one) ------------------
UP_OP(1) = INV_OP(1); % Acetic acid, without water, in 98% solution ...
    state {RER}| acetaldehyde oxidation | Alloc Def, U
UP_OP(2) = 0; % Acetic acid, without water, in 98% solution state ...
    {RER}| oxidation of butane | Alloc Def, U
UP_OP(3) = 0; % Acetic acid, without water, in 98% solution state ...
    {RER}| acetic acid production, product in 98% solution state | ...
    Alloc Def, U
UP_OP(4) = INV_OP(2); % Methanol {GLO}| production | Alloc Def, U
UP_OP(5) = INV_OP(3); % Iron (III) chloride, without water, in 40% ...
    solution state {CH}| iron (III) chloride production, product in 40% ...
    solution state | Alloc Def, U
UP_OP(6) = INV_OP(4); % Sodium hypochlorite, without water, in 15% ...
    solution state {RER}| sodium hypochlorite production, product in ...
    15% solution state | Alloc Def, U
% ------------------------ Electricity ------------------------
% Electricity source percentages are based on the state of Illinois
103 UP_OP(7) = 0.028 * INV_OP(5); % Electricity, natural gas, at power ... plant/US U
104 UP_OP(8) = 0.465 * INV_OP(5); % Electricity, hard coal, at power ... plant/US U
105 UP_OP(9) = 0.001 * INV_OP(5); % Electricity, hydropower, at pumped ... storage power plant/US U
106 UP_OP(10) = 0; % Electricity, hydropower, at power plant/CH U
107 UP_OP(11) = 0.001 * INV_OP(5); % Electricity, high voltage {GB}| ... electricity production, oil | Alloc Def, U
108 UP_OP(12) = 0.478 * INV_OP(5); % Electricity, nuclear, at power ... plant/US U
109 UP_OP(13) = 0.026 * INV_OP(5); % Electricity, at wind power plant ... 800KW/RER U
110 UP_OP(14) = 0.001 * INV_OP(5); % Electricity, high voltage {CH}| ... treatment of municipal solid waste, incineration | Alloc Def, U
111 % -------------------------------- Chlorine(pick one) --------------------------------
112 UP_OP(15) = INV_OP(6); % Chlorine, gaseous {RER}| chlor-alkali ... electrolysis, membrane cell | Alloc Def, U
113 UP_OP(16) = 0; % Chlorine, gaseous {RER}| chlor-alkali electrolysis, ... diaphragm cell | Alloc Def, U
114 UP_OP(17) = INV_OP(6); % Chlorine, gaseous {RER}| chlor-alkali ... electrolysis, mercury cell | Alloc Def, U
115
116 UP_OP(18) = INV_OP(7); % Methyl methacrylate {RER}| production | Alloc ... Def, U
117 UP_OP(19) = INV_OP(8); % Disposal, inert waste, 5% water, to inert ... material landfill/CH U
118 UP_OP(20) = INV_OP(9); % Citric acid {RER}| production | Alloc Def, U
119
120 % --> Ecoinvent 3.0 (TRACI 2.0)
121 CF_OP = [CF_ozo_op, CF_gwm_op, CF_smg_op, CF_acd_op, CF_eut_op, ... 
122 CF_car_op, CF_nca_op, CF_rsp_op, CF_ect_op];
123 UP_OP_matrix = [UP_OP, UP_OP, UP_OP, UP_OP, UP_OP, UP_OP, UP_OP, ... 
124 UP_OP];
125 IMPACT_OP = UP_OP_matrix .* CF_OP ./ V_treated;
% Impacts from Direction Emissions

% Characterization factors (CF) for direct emissions (DE)
% DE = [COD; NH3; NH4; Org-N; P; PO4; CH4; CO2];
% --> Ecoinvent 3.0 (TRACI 2.0)

CF_ozo_DE = [0; 0; 0; 0; 0; 0; 0; 0];
CF_gwm_DE = [0; 0; 0; 0; 0; 25; 1];
CF_smg_DE = [0; 0; 0; 0; 0; 0.014379487; 0];
CF_acd_DE = [0; 0; 0; 0; 0; 0; 0; 0];
CF_eut_DE = [0.05; 0.7793; 0.7793; 0; 0; 2.38; 0; 0];
CF_car_DE = [0; 0; 0; 0; 0; 0; 0; 0];
CF_nca_DE = [0; 0; 0; 0; 0; 0; 0; 0];
CF_rsp_DE = [0; 0; 0; 0; 0; 0; 0; 0];
CF_ect_DE = [0; 0; 0; 0; 0; 0; 0; 0];

CF_DE = [CF_ozo_DE, CF_gwm_DE, CF_smg_DE, CF_acd_DE, CF_eut_DE, ...
    CF_car_DE, CF_nca_DE, CF_rsp_DE, CF_ect_DE]; % characterization ...
    factor matrix
DEmis_matrix = [DEmis, DEmis, DEmis, DEmis, DEmis, DEmis, DEmis, ...
    DEmis]; % unit process matrix
IMPACT_DE = DEmis_matrix .* CF_DE ./ V_treated; % Construction impact ... 
    from each unit process

% Avoided Impacts
UP_avoided = zeros(20,1); % Ecoinvent unit process matrix

% --------------------------------- Electricity ---------------------------------
% Electricity source percentages are based on the state of Illinois
UP_avoided(7) = 0.028 * E_offset_kWh; % Electricity, natural gas, at ... 
    power plant/US U
UP_avoided(8) = 0.465 * E_offset_kWh; % Electricity, hard coal, at ... 
    power plant/US U
UP_avoided(9) = 0.001 * E_offset_kWh; % Electricity, hydropower, at ... 
    pumped storage power plant/US U
UP_avoided(10) = 0; % Electricity, hydropower, at power plant/CH U
UP_avoided(11) = 0.001 * E_offset_kWh; % Electricity, high voltage ... {GB} | electricity production, oil | Alloc Def, U

UP_avoided(12) = 0.478 * E_offset_kWh; % Electricity, nuclear, at power ... plant/US U

UP_avoided(13) = 0.026 * E_offset_kWh; % Electricity, at wind power ... plant 800kW/RER U

UP_avoided(14) = 0.001 * E_offset_kWh; % Electricity, high voltage ... {CH} | treatment of municipal solid waste, incineration | Alloc Def, U

CF_OP = [CF_ozo_op, CF_gwm_op, CF_smg_op, CF_acd_op, CF_eut_op, ... CF_car_op, CF_nca_op, CF_rsp_op, CF_ect_op];

UP_avoided_matrix = [UP_avoided, UP_avoided, UP_avoided, UP_avoided, ... UP_avoided, UP_avoided, UP_avoided, UP_avoided, UP_avoided];

IMPACT_avoided = - UP_avoided_matrix .* CF_OP ./ V_treated;
end

Listing B.3: Execution Script

clc; clear

%% Decision variables
J = 8.5; % [L/m^2-hr]

TMP_high = 25; % [psi]

TMP_low = 20; % [psi]

OL_AF = 5; % [g-COD/L-d] or [kg/m^3-day]

HL_AF = 10; % [m/hr]

OL_AER = 2; % [g-COD/L-d] or [kg/m^3-day]

HL_AER = 2; % [m/hr]
HRT = 10; % [hr]

N_train = 7;

IRR = 1;

% Assign values to decision variables
% if strcmp(step_A, 'CSTR') && strcmp(step_B, 'Submerged') && ...
    DVariable_1 = [J, TMP_high, N_train, IRR];
elseif strcmp(step_A, 'CSTR') && strcmp(step_B, 'Submerged') && ...
    DVariable_2 = [J, TMP_low, N_train, IRR];
elseif strcmp(step_A, 'CSTR') && strcmp(step_B, 'Cross-flow') && ...
    DVariable_3 = [J, TMP_high, N_train, IRR, HRT];
elseif strcmp(step_A, 'CSTR') && strcmp(step_B, 'Cross-flow') && ...
    DVariable_4 = [J, TMP_low, N_train, IRR, HRT];
elseif strcmp(step_A, 'AF') && strcmp(step_A1, 'none')
    DVariable_5 = [J, TMP_high, OL_AF, HL_AF, IRR];
elseif strcmp(step_A, 'AF') && strcmp(step_A1, '+GAC')
    DVariable_6 = [J, TMP_low, OL_AF, HL_AF, IRR];
elseif strcmp(step_A, 'AF') && strcmp(step_A1, '+AER')
    DVariable_7 = [J, TMP_low, OL_AF, HL_AF, IRR, OL_AER, HL_AER];
end

% Uncertainty parameters
Q_mgd = 20; % [mgd]

S_SO = 300; % [mg-COD/L] or [g/m^3]

X_SO = 100; % [mg-COD/L] or [g/m^3]

UParameter = [Q_mgd, S_SO, X_SO];
%% Inventory Analysis
[INV_CON_1, INV_OP_1, DEmis_1, Power_pct_1, E_input_kWh_1, ... 
  E_offset_kWh_1, V_treated_1, Output_cost_1] = LCI_anMBR('CSTR', ... 
  'none', 'Submerged', 'HF', 'PET', DVariable_1, UParameter);

%% Impact Assessment
[IMPACT_CON_1, IMPACT_OP_1, IMPACT_DE_1, IMPACT_avoided_1] = ... 
  Impact_Assessment (INV_CON_1, INV_OP_1, DEmis_1, E_offset_kWh_1, ... 
  V_treated_1);

% Total Impact (construction + operation)
CON_TOT_1 = sum(IMPACT_CON_1);
OP_TOT_1 = sum(IMPACT_OP_1);
IMPACT_TOT_1 = sum(IMPACT_CON_1) + sum(IMPACT_OP_1) + sum(IMPACT_DE_1);

%% Impact by Sources
% Construction phase
Concrete_pct_1 = (IMPACT_CON_1(1,:)) ./ IMPACT_TOT_1;
Steel_pct_1 = (IMPACT_CON_1(2,:) + IMPACT_CON_1(8,:)) ./ IMPACT_TOT_1;
Excavation_pct_1 = (IMPACT_CON_1(18,:)) ./ IMPACT_TOT_1;
CON_MISC_pct_1 = (sum(IMPACT_CON_1(3:7,:)) + sum(IMPACT_CON_1(9:17,:)) ... 
  + sum(IMPACT_CON_1(19:39,:))) ./ IMPACT_TOT_1;

% Operation phase
Pumping_PERM_pct_1 = (Power_pct_1(1) * sum(IMPACT_OP_1(7:14,:))) ./ ... 
  IMPACT_TOT_1;
Pumping_IR_pct_1 = (Power_pct_1(2) * sum(IMPACT_OP_1(7:14,:))) ./ ... 
  IMPACT_TOT_1;
Sparging_pct_1 = (Power_pct_1(3) * sum(IMPACT_OP_1(7:14,:))) ./ ... 
  IMPACT_TOT_1;
Pumping_CHEM_pct_1 = (Power_pct_1(4) * sum(IMPACT_OP_1(7:14,:))) ./ ... 
  IMPACT_TOT_1;
OP_MISC_pct_1 = (sum(IMPACT_OP_1(1:6,:)) + sum(IMPACT_OP_1(15:20,:)) ... 
  ./ IMPACT_TOT_1;
Energy.TOT_1 = sum(IMPACT.OP_1(7:14,:));

% Direct emission
DE_pct_1 = sum(IMPACT.DE_1) ./ IMPACT.TOT_1;

% Avoided Energy
Avoided_pct_1 = sum(IMPACT.avoided_1) ./ IMPACT.TOT_1;

Impact_source_pct_1 = [Concrete_pct_1; Steel_pct_1; Excavation_pct_1; ...
CON_MISC_pct_1; ...
Pumping_PERM_pct_1; Pumping_IR_pct_1; Sparging_pct_1; ...
Pumping.CHEM.pct_1; OP_MISC.pct_1; DE_pct_1; Avoided_pct_1];

% Impact by sources
barExtended(Impact_source_pct_1);

Impact_Categ = {'OZO';'GWM';'SMG';'ACD';...
' EUT'; 'CAR';'NON-CAR';'RSP';...
' ECOTOX'};

set(gca,'xticklabel',Impact_Categ);

legend('Concrete', 'Steel', 'Excavation', 'Construction Misc.', ...
'Permeate Pumping', 'Recirculation Pumping', 'Gas Sparging', ...
'Chemical Pumping', 'Operation Misc.', 'Direction Emissions', ...
'Avoided Energy', 'Location', 'NorthEastOutside');

% System 2: CSTR + submerged (hollow fiber) + GAC

disp(' System 2');

% LCI

[INV.CON_2, INV.OP_2, DEmis_2, Power_pct_2, E_input_kWh_2, ...
E.offset_kWh_2, V.treated_2] = LCI.anMBR('CSTR', '+GAC', ...
'Submerged', 'HF', 'PET', DVariable_2, UParameter);

% LCI --> Impact
[IMPACT_CON_2, IMPACT_OP_2, IMPACT_DE_2, IMPACT_avoided_2] = ... 
    Impact_Assessment (INV_CON_2, INV_OP_2, DEmis_2, E_offset_kWh_2, ... 
    V_treated_2);

% Total Impact (construction + operation)
CON_TOT_2 = sum(IMPACT_CON_2);
OP_TOT_2 = sum(IMPACT_OP_2);
IMPACT_TOT_2 = sum(IMPACT_CON_2) + sum(IMPACT_OP_2) + sum(IMPACT_DE_2);

% Impact by Sources
% Construction phase
Concrete_pct_2 = (IMPACT_CON_2(1,:)) ./ IMPACT_TOT_2;
Steel_pct_2 = (IMPACT_CON_2(2,:) + IMPACT_CON_2(8,:)) ./ IMPACT_TOT_2;
Excavation_pct_2 = (IMPACT_CON_2(18,:)) ./ IMPACT_TOT_2;
CON_MISC_pct_2 = (sum(IMPACT_CON_2(3:7,:)) + sum(IMPACT_CON_2(9:17,:)) ... 
    + sum(IMPACT_CON_2(19:39,:))) ./ IMPACT_TOT_2;

% Operation phase
Pumping_PERM_pct_2 = (Power_pct_2(1) * sum(IMPACT_OP_2(7:14,:))) ./ ... 
    IMPACT_TOT_2;
Pumping_IR_pct_2 = (Power_pct_2(2) * sum(IMPACT_OP_2(7:14,:))) ./ ... 
    IMPACT_TOT_2;
Pumping_CHEM_pct_2 = (Power_pct_2(3) * sum(IMPACT_OP_2(7:14,:))) ./ ... 
    IMPACT_TOT_2;
OP_MISC_pct_2 = (sum(IMPACT_OP_2(1:6,:)) + sum(IMPACT_OP_2(15:20,:))) ... 
    ./ IMPACT_TOT_2;

Energy_TOT_2 = sum(IMPACT_OP_2(7:14,:));

% Direct emission
DE_pct_2 = sum(IMPACT_DE_2) ./ IMPACT_TOT_2;

% Avoided Energy
Avoided_pct_2 = sum(IMPACT_avoided_2) ./ IMPACT_TOT_2;
Impact source pct_2 = [Concrete_pct_2; Steel_pct_2; Excavation_pct_2; ...  
    CON_MISC_pct_2; ...  
    Pumping_PERM_pct_2; Pumping_IR pct_2; Pumping_CHEM pct_2; ...  
    OP_MISC_pct_2; DE pct_2; Avoided pct_2];  
% Impact by sources  
barExtended(Impact source pct_2');  
Impact_Categ = {'OZO'; 'GWM'; 'SMG'; 'ACD'; ...  
    'EUT'; 'CAR'; 'NON-CAR'; 'RSP'; ...  
    'ECOTOX'};  
set(gca,'xticklabel',Impact_Categ);  
legend('Concrete', 'Steel', 'Excavation', 'Construction Misc.', ...  
    'Permeate Pumping', 'Recirculation Pumping', 'Chemical Pumping', ...  
    'Operation Misc.', 'Direction Emissions', 'Avoided Energy', ...  
    'Location', 'NorthEastOutside');  

%% System 3: CSTR + Cross-flow (Multi-tube)  
disp(' System 3');  
%% Inventory Analysis  
[INV CON_3, INV OP_3, DEmis_3, Power pct_3, E input kWh_3, ...  
    E offset kWh_3, V treated_3, Output cost_3] = LCI_anMBR('CSTR', ...  
    'none', 'Cross-flow', 'MT', 'PET', DVariable_3, UParameter);  

%% Impact Assessment  
[IMPACT CON_3, IMPACT OP_3, IMPACT DE_3, IMPACT avoided_3] = ...  
    Impact Assessment (INV CON_3, INV OP_3, DEmis_3, E offset kWh_3, ...  
    V treated_3);  

% Total Impact (construction + operation)  
CON TOT 3 = sum(IMPACT CON_3);  
OP TOT 3 = sum(IMPACT OP_3);  
IMPACT TOT 3 = sum(IMPACT CON_3) + sum(IMPACT OP_3) + sum(IMPACT DE_3);  

% Impact by Sources
% Construction phase
Concrete_pct_3 = (IMPACT_CON_3(1,:)) ./ IMPACT_TOT_3;
Steel_pct_3 = (IMPACT_CON_3(2,:) + IMPACT_CON_3(8,:)) ./ IMPACT_TOT_3;
Excavation_pct_3 = (IMPACT_CON_3(18,:)) ./ IMPACT_TOT_3;
CON_MISC_pct_3 = (sum(IMPACT_CON_3(3:7,:)) + sum(IMPACT_CON_3(9:17,:)) ...
    + sum(IMPACT_CON_3(19:39,:))) ./ IMPACT_TOT_3;

% Operation phase
Pumping_PERM_pct_3 = (Power_pct_3(1) * sum(IMPACT_OP_3(7:14,:))) ./ ...
    IMPACT_TOT_3;
Pumping_IR_pct_3 = (Power_pct_3(2) * sum(IMPACT_OP_3(7:14,:))) ./ ...
    IMPACT_TOT_3;
Pumping_R pct_3 = (Power_pct_3(3) * sum(IMPACT_OP_3(7:14,:))) ./ ...
    IMPACT_TOT_3;
Pumping_CHEM pct_3 = (Power_pct_3(4) * sum(IMPACT_OP_3(7:14,:))) ./ ...
    IMPACT_TOT_3;
OP_MISC pct_3 = (sum(IMPACT_OP_3(1:6,:)) + sum(IMPACT_OP_3(15:20,:))) ...
    ./ IMPACT_TOT_3;
E nergy_TOT_3 = sum(IMPACT_OP_3(7:14,:));

% Direct emission
DE_pct_3 = sum(IMPACT_DE) ./ IMPACT_TOT_3;

% Avoided Energy
Avoided_pct_3 = sum(IMPACT_avoided_3) ./ IMPACT_TOT_3;

Impact_source_pct_3 = [Concrete_pct_3; Steel_pct_3; Excavation_pct_3; ...
    CON_MISC_pct_3; ...
    Pumping_PERM_pct_3; Pumping_IR_pct_3; Pumping_R_pct_3; ...
    Pumping_CHEM pct_3; OP_MISC pct_3; DE pct_3; Avoided pct_3];

% Impact by sources
barExtended(Impact_source_pct_3);
Impact_Categ = {'OZO';'GWM';'SMG';'ACD';...
    'EUT'; 'CAR';'NON-CAR';'RSP';...
    'ECOTOX'};
```matlab
set(gca,'xticklabel','Impact_Categ');
legend('Concrete', 'Steel', 'Excavation', 'Construction Misc.', ...
'Permeate Pumping', 'Recirculation Pumping', 'Retentate Pumping', ...
'Chemical Pumping', 'Operation Misc.', 'Direction Emissions', ...
'Avoided Energy', 'Location', 'NorthEastOutside');

%% System 5: AF + Crossflow (Multi-tube)
disp(' System 5');

%% LCI
[INV_CON_5, INV_OP_5, DEmis_5, Power_pct_5, E_input_kWh_5, ...
E_offset_kWh_5, V_treated_5, Output_cost_5] = LCI_anMBR('AF', ...
'none', 'Cross-flow', 'MT', 'PET', DVariable_5, UParameter);

%% LCI --> Impact
[IMPACT_CON_5, IMPACT_OP_5, IMPACT_DE_5, IMPACT_avoided_5] = ...
Impact_Assessment (INV_CON_5, INV_OP_5, DEmis_5, E_offset_kWh_5, ...
V_treated_5);

% Total Impact (construction + operation)
CON_TOT_5 = sum(IMPACT_CON_5);
OP_TOT_5 = sum(IMPACT_OP_5);
IMPACT_TOT_5 = sum(IMPACT_CON_5) + sum(IMPACT_OP_5) + sum(IMPACT_DE_5);

%% Impact by Sources
% Construction phase
Concrete_pct_5 = (IMPACT_CON_5(1,:)) ./ IMPACT_TOT_5;
Steel_pct_5 = (IMPACT_CON_5(2,:) + IMPACT_CON_5(8,:)) ./ IMPACT_TOT_5;
Excavation_pct_5 = (IMPACT_CON_5(18,:)) ./ IMPACT_TOT_5;
CON_MISC_pct_5 = (sum(IMPACT_CON_5(3:7,:)) + sum(IMPACT_CON_5(9:17,:)) ...
+ sum(IMPACT_CON_5(19:39,:))) ./ IMPACT_TOT_5;

% Operation phase
```
Pumping_LIFT_pct_5 = (Power_pct_5(1) * sum(IMPACT_OP_5(7:14,:))) ./ IMPACT_TOT_5;
Pumping_PERM_pct_5 = (Power_pct_5(2) * sum(IMPACT_OP_5(7:14,:))) ./ IMPACT_TOT_5;
Pumping_IR_pct_5 = (Power_pct_5(3) * sum(IMPACT_OP_5(7:14,:))) ./ IMPACT_TOT_5;
Pumping_R_pct_5 = (Power_pct_5(4) * sum(IMPACT_OP_5(7:14,:))) ./ IMPACT_TOT_5;
Pumping_CHEM_pct_5 = (Power_pct_5(5) * sum(IMPACT_OP_5(7:14,:))) ./ IMPACT_TOT_5;
OP_MISC_pct_5 = (sum(IMPACT_OP_5(1:6,:)) + sum(IMPACT_OP_5(15:20,:))) ./ IMPACT_TOT_5;

Energy_TOT_5 = sum(IMPACT_OP_5(7:14,:));

% Direct emission
DE_pct_5 = sum(IMPACT_DE_5) ./ IMPACT_TOT_5;

% Avoided Energy
Avoided_pct_5 = sum(IMPACT_avoided_5) ./ IMPACT_TOT_5;

Impact_source_pct_5 = [Concrete_pct_5; Steel_pct_5; Excavation_pct_5; ...
CON_MISC_pct_5; ...
Pumping_LIFT_pct_5; Pumping_PERM_pct_5; Pumping_IR_pct_5; ...
Pumping_R_pct_5; Pumping_CHEM_pct_5; OP_MISC_pct_5; DE_pct_5; ...
Avoided_pct_5];

% Impact by sources
barExtended(Impact_source_pct_5);
Impact_Categ = {'OZO';'GWM';'SMG';'ACD';
'EUT'; 'CAR';'NON-CAR';'RSP';...
'ECOTOX'};
set(gca,'xticklabel',Impact_Categ);
legend('Concrete', 'Steel', 'Excavation', 'Construction Misc.','.}

'Lift Pumping', 'Permeate Pumping', 'Recirculation Pumping', ...
'Retentate Pumping', 'Chemical Pumping', 'Operation Misc.', ...
'Direction Emissions', 'Avoided Energy', 'Location', ...
'NorthEastOutside');

%% System 6: AF + AER + Crossflow (Multi-tube)

disp(' System 6');

%% LCI

[INV_CON_6, INV_OP_6, DEmis_6, Power_pct_6, E_input_kWh_6, ...
  E_offset_kWh_6, V_treated_6, Output_cost_6] = LCI_anMBR('AF', ...
  '+AER', 'Cross-flow', 'MT', 'PET', DVariable_7, UParameter);

%% LCI --> Impact

[IMPACT_CON_6, IMPACT_OP_6, IMPACT_DE_6, IMPACT_avoided_6] = ...
  Impact_Assessment (INV_CON_6, INV_OP_6, DEmis_6, E_offset_kWh_6, ... 
  V_treated_6);

% Total Impact (construction + operation)

CON_TOT_6 = sum(IMPACT_CON_6);  
OP_TOT_6 = sum(IMPACT_OP_6);  
IMPACT_TOT_6 = sum(IMPACT_CON_6) + sum(IMPACT_OP_6) + sum(IMPACT_DE_6);

% Impact by Sources

% Construction phase

Concrete_pct_6 = (IMPACT_CON_6(1,:)) ./ IMPACT_TOT_6;  
Steel_pct_6 = (IMPACT_CON_6(2,:) + IMPACT_CON_6(8,:)) ./ IMPACT_TOT_6; 
Excavation_pct_6 = (IMPACT_CON_6(18,:)) ./ IMPACT_TOT_6; 
CON_MISC_pct_6 = (sum(IMPACT_CON_6(3:7,:)) + sum(IMPACT_CON_6(9:17,:)) ... 
  + sum(IMPACT_CON_6(19:39,:))) ./ IMPACT_TOT_6;

% Operation phase

Pumping_LIFT_pct_6 = (Power_pct_6(1) + sum(IMPACT_OP_6(7:14,:))) ./ ...
  IMPACT_TOT_6;
Pumping\_PERM\_pct\_6 = (Power\_pct\_6(2) * sum(IMPACT\_OP\_6(7:14,:))) ./ ... IMPACT\_TOT\_6;

Pumping\_IR\_pct\_6 = (Power\_pct\_6(3) * sum(IMPACT\_OP\_6(7:14,:))) ./ ... IMPACT\_TOT\_6;

Pumping\_R\_pct\_6 = (Power\_pct\_6(4) * sum(IMPACT\_OP\_6(7:14,:))) ./ ... IMPACT\_TOT\_6;

Pumping\_CHEM\_pct\_6 = (Power\_pct\_6(5) * sum(IMPACT\_OP\_6(7:14,:))) ./ ... IMPACT\_TOT\_6;

OP\_MISC\_pct\_6 = (sum(IMPACT\_OP\_6(1:6,:)) + sum(IMPACT\_OP\_6(15:20,:))) ... ./ IMPACT\_TOT\_6;

Energy\_TOT\_6 = sum(IMPACT\_OP\_6(7:14,:));

% Direct emission
DE\_pct\_6 = sum(IMPACT\_DE\_6) ./ IMPACT\_TOT\_6;

% Avoided Energy
Avoided\_pct\_6 = sum(IMPACT\_avoided\_6) ./ IMPACT\_TOT\_6;

Impact\_source\_pct\_6 = [Concrete\_pct\_6; Steel\_pct\_6; Excavation\_pct\_6; ... CON\_MISC\_pct\_6; ... Pumping\_LIFT\_pct\_6; Pumping\_PERM\_pct\_6; Pumping\_IR\_pct\_6; ... Pumping\_R\_pct\_6; Pumping\_CHEM\_pct\_6; OP\_MISC\_pct\_6; DE\_pct\_6; ... Avoided\_pct\_6];

%% Impact by sources
barExtended(Impact\_source\_pct\_6');

Impact\_Categ = {'OZO'; 'GWM'; 'SMG'; 'ACD'; ... 'EUT'; 'CAR'; 'NON-CAR'; 'RSP'; ... 'ECOTOX'};

set(gca,'xticklabel',Impact\_Categ);

legend('Concrete', 'Steel', 'Excavation', 'Construction Misc.', ... 'Lift Pumping', 'Permeate Pumping', 'Recirculation Pumping', ... 'Retentate Pumping', 'Chemical Pumping', 'Operation Misc.', ... 'Direction Emissions', 'Avoided Energy', 'Location', ... 'NorthEastOutside');
%% Plot (3): Total Impact with error bars

figure

bar([IMPACT_TOT_1 ./IMPACT_TOT_1; IMPACT_TOT_2 ./IMPACT_TOT_1; ...
    IMPACT_TOT_3 ./IMPACT_TOT_1; IMPACT_TOT_5 ./IMPACT_TOT_1; ...
    IMPACT_TOT_6 ./IMPACT_TOT_1']);

hold

bar([sum(IMPACT_avoided_1) ./IMPACT_TOT_1; sum(IMPACT_avoided_2) ...
    ./IMPACT_TOT_1; sum(IMPACT_avoided_3) ./IMPACT_TOT_1; ...
    sum(IMPACT_avoided_5) ./IMPACT_TOT_1; sum(IMPACT_avoided_6) ...
    ./IMPACT_TOT_1']);

Impact_Categ = {'OZO';'GWM';'SMG';'ACD';...
    'EUT'; 'CAR';'NON-CAR';'RSP';...
    'ECOTOX'};

set(gca,'xticklabel',Impact_Categ,'fontSize',10);

legend('System 1', 'System 2', 'System 3', 'System 4', 'System 5', 5, ...
    'Location', 'NorthEastOutside')

hold off

% Construction Inventory comparison

figure

bar([CON_TOT_1 ./CON_TOT_1; CON_TOT_2 ./CON_TOT_1; CON_TOT_3 ...
    ./CON_TOT_1; CON_TOT_5 ./CON_TOT_1; CON_TOT_6 ./CON_TOT_1']);

Impact_Categ = {'OZO';'GWM';'SMG';'ACD';...
    'EUT'; 'CAR';'NON-CAR';'RSP';...
    'ECOTOX'};

set(gca,'xticklabel',Impact_Categ,'fontSize',10);

legend('System 1', 'System 2', 'System 3', 'System 4', 'System 5', 5, ...
    'Location', 'NorthEastOutside')

hold off

% Operational Inventory comparison

figure

bar([OP_TOT_1 ./OP_TOT_1; OP_TOT_2 ./OP_TOT_1; OP_TOT_3 ./OP_TOT_1; ...
    OP_TOT_5 ./OP_TOT_1; OP_TOT_6 ./OP_TOT_1']);
Listing B.4: CSTR

```matlab
function [D_train, L_train, W_train, W_Ntrains, W_PB, L_BB, VWC, VSC, ...
    VEX] = CSTR(Q_mgd, HRT, N_train)

% Input:
% Influent flow rate, Q_mgd [mgd]
% Hydraulic retention time, HRT [hr]
% Number of trains, N_train

% --> CSTR Design
W_train = 21; % [ft] Width of one train
D_train = 12; % [ft] Depth of one train
Q_cfh = Q_mgd * 133681 / 24; % [ft^3/hr] unit conversion
```
\[
L_{\text{train}} = \frac{Q_{\text{cfh}} \times \text{HRT}}{N_{\text{train}} \times W_{\text{train}} \times D_{\text{train}}}; \quad \text{[ft]} \quad \text{Length of one train}
\]

% Width of pump building, \(W_{\text{PB}}\) [ft] (based on Hazen & Sawyer data)
\[
N_{\text{eq}} = \frac{L_{\text{train}}}{((1 + 8/12) + (3 + 4/12))}; \quad \text{based on CSTR with submerged membrane}
\]

if \(N_{\text{eq}} \geq 5 \land N_{\text{eq}} \leq 10\)
\[
W_{\text{PB}} = 27 + 4/12;
\]
elseif \(N_{\text{eq}} \geq 11 \land N_{\text{eq}} \leq 16\)
\[
W_{\text{PB}} = 29 + 6/12;
\]
elseif \(N_{\text{eq}} \geq 17 \land N_{\text{eq}} \leq 22\)
\[
W_{\text{PB}} = 31 + 8/12;
\]
elseif \(N_{\text{eq}} \geq 23 \land N_{\text{eq}} \leq 28\)
\[
W_{\text{PB}} = 35;
\]
elseif \(N_{\text{eq}} \geq 29\)
\[
W_{\text{PB}} = 38 + 4/12;
\]
end

% Width of blower building, \(W_{\text{BB}}\) [ft]
\[
\text{if } N_{\text{eq}} \leq 18
\]
\[
W_{\text{BB}} = 18 + 8/12;
\]
else
\[
W_{\text{BB}} = 22;
\]
end

% Length of blower building, \(L_{\text{BB}}\) [ft]
\[
\text{if } N_{\text{eq}} \leq 18
\]
\[
L_{\text{BB}} = 69 + 6/12;
\]
else
\[
L_{\text{BB}} = 76 + 8/12;
\]
end

% --> Concrete
% (assume walls are built on slabs)
% Concrete wall thickness [ft]
if D_train < 12
    t_wall = 1; % Minimum wall thickness = 12 inches
else
    t_wall = 1 + (D_train - 12)/12; % Adding an inch for every foot of ... depth over 12 ft
end

% Concrete slab thickness [ft]
t_slab = t_wall + 2/12; % Slab thickness = wall thickness + 2 inches

% Concrete Part I [ft^3] - Distribution Channel
W_dist = 4.5; % [ft] Width of distribution channel
W_N_trains = (W_train + 2 * t_wall) * N_train - t_wall * (N_train - 1);
VWC_I = D_train * t_wall * (2 * W_N_trains + 2 * W_dist);
VSC_I = W_N_trains * (W_dist + 2 * t_wall) * t_slab;

% Concrete Part II [ft^3] - Membrane Trains
VWC_II = D_train * t_wall * (N_train + 1) * L_train;
VSC_II = N_train * (D_train + 2.4 + 4.81 + 2.4 + 7.26) * t_slab * L_train;

% Concrete Part III [ft^3] - Effluent Channel & Pump/Blower House
W_eff = 5; % [ft] Width of effluent channel
VWC_III = D_train * t_wall * (2 * W_N_trains + 2 * W_eff) + D_train * ...
                  t_wall * (2 * W_N_trains + 2 * W_PB + 2 * W_BB);
VSC_III = W_N_trains * (W_eff + 2 * t_wall) + t_slab + W_N_trains * ...
               (W_PB + t_wall + W_BB) * t_slab;

% Wet Well (for mix liquor storage)
D_WW = 12; % [ft] Depth of wet well
W_WW = 8; % [ft] Width of wet well
L_WW = 8; % [ft] Length of wet well
VWC_well = D_WW * (L_WW * t_wall + W_WW * t_wall + 4 * t_wall);
VSC_well = t_slab * (L_WW + 2 * t_wall) * (W_WW + 2 * t_wall);

% Total Volume of Wall Concrete [ft^3]
VWC = VWC_I + VWC_II + VWC_III + VWC_well;
% Total Volume of Slab Concrete [ft^3]
VSC = VSC_I + VSC_II + VSC_III + VSC_well;

% --> Excavation
SL = 1.5; % Slope = horizontal/vertical
CA = 3; % [ft] Construction Access

% Volume of excavation of membrane trains [ft^3]
Area_B_train = (W_dist + L_train + W_eff + 2 * CA) * (W_N_trains + 2 * CA); % top area
Area_T_train = (W_dist + L_train + W_eff + 2 * CA + D_train * SL) * ...
(W_N_trains + 2 * CA + D_train * SL); % bottom area
VEX_train = 0.5 * (Area_B_train + Area_T_train) * D_train;

% Volume of excavation of pump/blower building [ft^3]
Area_B_PB = (W_PB + W_BB + 2 * CA) * (W_N_trains + 2 * CA);
Area_T_P = (W_PB + W_BB + 2 * CA + D_train * SL) * (W_N_trains + 2 * CA ... + D_train * SL);
VEX_PB = 0.5 * (Area_B_PB + Area_T_P) * D_train;

% Total Volume of Excavation [ft^3]
VEX = VEX_train + VEX_PB;
end

Listing B.5: Anaerobic Filter

function [V_m_AF_ft, D_AF_ft, Dia_AF_ft, N_AF, VWC_AF, VSC_AF, VEX] = ...
    ANA_Filter(Q_mgd, S_SO, X_SO, OL_AF, HL_AF, R_AF)
% Input:
    % Influent flow rate, Q_mgd [mgd]
    % Influent readily biodegradable (soluble) substrate concentration, ...
    S_SO [mg-BOD5/L or g/m^3]
% Influent slowly biodegradable (particulate) substrate ...
    concentration, X_SO [mg-BOD5/L or g/m^3]
% Organic loading rate, OL_AF [kg-BOD5/m^3-day]
% Hydraulic loading rate, HL_AF [m^3/m^2-hr]
% Recirculation ratio, R_AF

% Anaerobic Filter Design
N_AF = 2;  % Initialize number of ANA filters

% Volume of packing media in each filter, V_m_AF [m^3] (1000 = 'g' to ... 'kg' unit conversion factor)
Q_cmd = Q_mgd * 3785.41178;  % [m^3/day]
V_m_AF = (Q_cmd / N_AF) * (S_SO + X_SO) / OL_AF / 1000;

% X-sectional area of each filter, A_AF [m^2]
Q_cmh = Q_cmd / 24;  % [m^3/hour]
A_AF = Q_cmh * (1 + R_AF) / N_AF / HL_AF;

% Diameter of each filter, Dia_AF [m]
Dia_AF = (4 * A_AF / pi) ^ 0.5;

% Depth of each ANA filter, D_AF [m]
D_AF = V_m_AF / A_AF;

while D_AF > 6  % Maximum depth assumption [m]
    R_AF = R_AF + 0.1;
    A_AF = Q_cmh * (1 + R_AF) / N_AF / HL_AF;
    Dia_AF = (4 * A_AF / pi) ^ 0.5;
    % Check if more than 1 filter is needed
    while Dia_AF > 12  % Maximum diameter assumption [m]
        N_AF = N_AF + 1;
        A_AF = Q_cmh * (1 + R_AF) / N_AF / HL_AF;
        Dia_AF = (4 * A_AF / pi) ^ 0.5;
    end
V_m_AF = (Q_cmd / N_AF) * (S_SO + X_SO) / OL_AF / 1000;
D_AF = V_m_AF / A_AF;

% Unit conversion ('m' to 'ft')
Dia_AF_ft = Dia_AF * 3.28084; % [ft]
D_AF_ft = D_AF * 3.28084; % [ft]
V_m_AF_ft = V_m_AF * 3.28084^3; % [ft^3]

% --> Concrete
% Concrete of anaerobic filter
FB_AF = 3; % [ft] freeboard
wall_AF = 6/12; % [ft] wall thickness
slab_AF = 8/12; % [ft] slab thickness

% External wall (wall concrete), VWC_E_AF [ft^3]
VWC_E_AF = wall_AF * pi * Dia_AF_ft * (D_AF_ft + FB_AF);

% Floor (slab concrete), VSC_F_AF [ft^3]
VSC_F_AF = slab_AF * (pi/4) * Dia_AF_ft^2;

VWC_AF = N_AF * VWC_E_AF; % [ft^3] Volume of wall concrete
VSC_AF = N_AF * VSC_F_AF; % [ft^3] Volume of slab concrete

% --> Excavation
SL = 1.5; % Slope = horizontal/vertical
CA = 3; % [ft] Construction Access

% Excavation of Pump Building
PBL = 50; % [ft] Pump Building Length
PBW = 30; % [ft] Pump Building Width
PBD = 10; % [ft] Pump Building Depth
Area_B = (PBL + 2 * CA) * (PBW + 2 * CA); % [ft^2] Bottom Area of frustum
Area_T_P = (PBL + 2 * CA + PBW * SL) * (PBW + 2 * CA + PBD * SL); \text{[ft}^2\text{]} \text{ Top Area of frustum}

VEX_PB = 0.5 * (Area_B_P + Area_T_P) * PBD; \text{[ft}^2\text{]} \text{ Volume of excavation of Pump Building}

VEX = VEX_PB; \text{[ft}^3\text{]} \text{ Total volume of excavation}

end

---

**Listing B.6: Aerobic Polishing Filter**

```matlab
function [V_m_AER_ft, D_AER_ft, Dia_AER_ft, N_AER, VWC_AER, VSC_AER, ... VEX] = AER_Filter(Q_mgd, S_SO, X_SO, OL_AER, HL_AER)
% Input:
% Influent flow rate, Q_mgd [mgd]
% Influent readily biodegradable (soluble) substrate concentration, ...
% S_SO [mg-BOD5/L or g/m^3]
% Influent slowly biodegradable (particulate) substrate ...
% concentration, X_SO [mg-BOD5/L or g/m^3]
% Organic loading rate, OL_AER [kg-BOD5/m^3-day]
% Hydraulic loading rate, HL_AER [m^3/m^2-hr]

N_AER = 2; \text{[m]} \text{ Initialize number of AER filters}

Removal_ANA = 0.95;

% Influent Water Parameters
S_SO_AER = S_SO * (1-Removal_ANA); \text{[mg-BOD5/L] redily biodegradable substrate (Assume 95% removal in ANA filter)}
X_SO_AER = X_SO * (1-Removal_ANA); \text{[mg/L] Slowly biodegradable (particulate) substrate concentration (Assume 95% removal in ANA filter)}
```
% Volume of packing media in each filter, $V_{m,AER}$ [m$^3$] (1000 = 'g' to ...
'kg' unit conversion factor)

```matlab
Q_cmd = Q_mgd * 3785.41178; % [m$^3$/day]
V_m_AER = (Q_cmd / N_AER) * (S_SO_AER + X_SO_AER) / OL_AER / 1000;

% X-sectional area of each filter, $A_{AER}$ [m$^2$]
Q_cmh = Q_cmd / 24; % [m$^3$/hour]
A_AER = Q_cmh / N_AER / HL_AER;

% Diameter of each filter, Dia_AER [m]
Dia_AER = (4 * A_AER / pi) ^ 0.5;

% Depth of each ANA filter, D_AER [m]
D_AER = V_m_AER / A_AER;
```

% Check if more than 1 filter is needed
```matlab
while Dia_AER > 12 % Maximum diameter assumption [m]
    N_AER = N_AER + 1;
    V_m_AER = (Q_cmd / N_AER) * (S_SO + X_SO) / OL_AER / 1000;
    A_AER = Q_cmh / N_AER / HL_AER;
    Dia_AER = (4 * A_AER / pi) ^ 0.5;
    D_AER = V_m_AER / A_AER;
end
```

% Unit conversion ('m' to 'ft')
```matlab
Dia_AER_ft = Dia_AER * 3.28084; % [ft]
D_AER_ft = D_AER * 3.28084; % [ft]
V_m_AER_ft = V_m_AER * 3.28084^3; % [ft$^3$]
```

% --> Concrete
% Concrete of anaerobic filter
FB_AER = 3; % [ft] freeboard
```
```
```matlab
```t_wall_AER = 6/12; % [ft] wall thickness
t_slab_AER = 8/12; % [ft] slab thickness
```
% External wall (wall concrete), VWC_E_AER [ft^3]
VWC_E_AER = t_wall_AER * pi * Dia_AER_ft * (D_AER_ft + FB_AER);

% Floor (slab concrete), VSC_F_AER [ft^3]
VSC_F_AER = t_slab_AER * (pi/4) * Dia_AER_ft^2;

VWC_AER = N_AER * VWC_E_AER; % [ft^3] Volume of wall concrete
VSC_AER = N_AER * VSC_F_AER; % [ft^3] Volume of slab concrete

% --> Excavation
SL = 1.5; % Slope = horizontal/vertical
CA = 3; % [ft] Construction Access

% Excavation of Pump Building
PBL = 50; % [ft] Pump Building Length
PBW = 30; % [ft] Pump Building Width
PBD = 10; % [ft] Pump Building Depth

Area_B_P = (PBL + 2 * CA) * (PBW + 2 * CA); % [ft^2] Bottom Area of frustum
Area_T_P = (PBL + 2 * CA + PBW * SL) * (PBW + 2 * CA + PBD * SL); % ...
            [ft^2] Top Area of frustum
VEX_PB = 0.5 * (Area_B_P + Area_T_P) * PBD; % [ft^2] Volume of ...
        excavation of Pump Building

VEX = VEX_PB; % [ft^3] Total volume of excavation
end

Listing B.7: Multi-Tube Membrane

function [M_memb_tot, N_SU, N_LU, Q_R_mgd] = Multi_Tube(Q_mgd, J, T_bw, ...
            VEL_xflow)
% Input:
% Flow rate, Q_mgd [mgd]
% Flux, J [L/m^2-hr]
% Backwashing time per day, T_bw [hr]
% Cross-flow velocity, VEL_xflow [m/s]

% Output:
% Mass of membrane material, M_memb_tot [kg]
% Number of small unit, N_SU (In this case, small unit refers to ... Pentair X-flow model AQFMBR 30 module)
% Number of large unit, N_LU_pt
% Retentate flow rate, Q_R_mgd [mgd]

% Assume Pentair X-flow model AQFMBR 30
% (Membrane information available at: % Info from ... http://onlinembr.info/Membrane%20process/Airlift.htm

J_m3pm2d = (J / 10^3) * 24; % [m^3/m^2-day] Membrane flux
 % unit conversion: [L/m^2-hr] to [m^3/m^2-day]

Q_cmd = Q_mgd * 3785.41178; % [m^3/day]
Q_bw_cmd = Q_cmd * T_bw / 24; % [m^3/day] Backwashing flow rate
A_rqdtot = (Q_cmd + Q_bw_cmd) / J_m3pm2d; % [ft^2] Total membrane area

A_module = 32; % [m^2] Membrane surface area per module (Pentair X-flow ... model AQFMBR 30)

N_SU_pLU = 30; % Number of small units per large unit (assume 30 ... Pentair X-flow model AQFMBR 30 modules)
A_LU = N_SU_pLU * A_module; % [ft^2] % Surface area of each large unit
N_LU = A_rqdtot / A_LU; % Total number of large units
N_SU = N_LU * N_SU_pLU; % Total number of small units

Q_xflow = 29.3 * VEL_xflow; % [m^3/hr] cross-flow flow rate per AQFMBR ... 30 module
Q_R_cmh = N_SU * Q_xflow; % [m^3/hr] Total retentate flow rate
Q_R_mgd = Q_R_cmh * 0.00634; % [mgd] unit conversion
Listing B.8: Flat Sheet Membrane

function [M_memb_tot, N_SU, N_LU_pt, A_LU] = Flat_Sheet(Q_mgd, J, ...
    N_train, T_bw)

% Input:
% Flow rate, Q_mgd [mgd]
% Flux, J [L/m^2-hr]
% Number of membrane trains, N_train
% Backwashing time per day, T_bw [hr]

% Output:
% Mass of membrane material, M_memb_tot [kg]
% Number of small unit, N_SU (In this case, small unit refers to ...
%   flat-sheet panel)
% Number of large unit, N_LU_pt
% Surface area of each large unit, A_LU [ft^2]

% Assume Kubota-RM515 for flat sheet membrane
\[ J_{fpd} = J \times 0.07874; \quad \text{[ft}^3/\text{ft}^2\text{-day]} \quad \text{Membrane flux} \]

\[
\text{unit conversion: 1 L/m}^2\text{-hr} = 0.07874 \text{ ft}^3/\text{ft}^2\text{-day}
\]

\[ Q_{cfd} = Q_{mgd} \times 133680.556; \quad \text{[ft}^3/\text{day}] \]

\[ Q_{bw_{cfd}} = Q_{cfd} \times T_{ bw} / 24; \quad \text{[ft}^3/\text{day}] \quad \text{Backwashing flow rate} \]

\[ A_{rqd_{tot}} = (Q_{cfd} + Q_{bw_{cfd}}) / J_{fpd}; \quad \text{[ft}^2] \quad \text{Total membrane area} \]

\[ A_{SU} = 1.45 \times 10.7639; \quad \text{[ft}^2] \quad \text{Membrane surface area of each small unit} \]

\[ N_{SU_{pLSU}} = 150; \quad \% \quad \text{Number of small units per large unit (assume 150-200 ... panels, Kubota-RM515)} \]

\[ A_{LU} = N_{SU_{pLSU}} \times A_{SU}; \quad \text{[ft}^2] \quad \text{Surface area of each large unit} \]

\[ N_{LU_{pt}} = \text{ceil}(A_{rqd_{tot}} / N_{ train} / A_{LU}); \quad \% \quad \text{Number of large units per ... membrane train} \]

\[ N_{SU} = N_{LU_{pt}} \times N_{ train} \times N_{SU_{pLSU}}; \quad \% \quad \text{Total number of small units} \]

\[
\text{Listing B.9: Hollow Fiber Membrane}
\]

\begin{verbatim}
function [M_memb_tot, N_SU, N_LU_pt, A_LU] = Hollow_Fiber(Q_mgd, J, ... 
    N_train, T_bw)
% Input:
% Flow rate, Q_mgd [mgd]
end
\end{verbatim}
% Flux, J [L/m^2-hr]
% Number of membrane trains, N_train
% Backwashing time per day, T_bw [hr]

% Output:
% Mass of membrane material, M_memb_tot [kg]
% Number of small unit, N_SU (In this case, small unit refers to ... Zenon-ZeeWeed*500D module)
% Number of large unit, N_LU_pt
% Surface area of each large unit, A_LU [ft^2]

% Assume Zenon-ZeeWeed*500D Cassette for hollow fiber membrane
% (Membrane module specs available ... at:http://www.gewater.com/products/zeeweed-500-membrane.html)

J_fpd = J * 0.07874; % [ft^3/ft^2-day] Membrane flux
% unit conversion: 1 L/m^2-hr = 0.07874 ft^3/ft^2-day

Q_cfd = Q_mgd * 133680.556; % [ft^3/day]
Q_bw_cfd = Q_cfd * T_bw / 24; % [ft^3/day] Backwashing flow rate
A_rq_d_tot = (Q_cfd + Q_bw_cfd) / J_fpd; % [ft^2] Total membrane area

A_SU = 370; % [ft^2] Membrane surface area of each small unit
N_SU_pLU = 44; % % Number of small units per large unit (assume 48 ...
    Zenon-ZeeWeed*500D modules)
A_LU = N_SU_pLU * A_SU; % [ft^2] Surface area of each large unit
N_LU_pt = ceil(A_rq_d_tot / N_train / A_LU); % Number of large units per ... membrane train
N_SU = N_LU_pt * N_train * N_SU_pLU; % Total number of small units

% Membrane Material
OD_fiber = 1.9 * 10^-3; % [m] Outer diameter of each membrane fiber
ID_fiber = 0.8 * 10^-3; % [m] Inner diameter of each membrane fiber
L_fiber = 2.198; % [m] Length of each fiber
A_fiber = L_fiber * pi * OD_fiber; % [m^2] Surface area of each fiber
\[ V_{\text{fiber}} = L_{\text{fiber}} \times \frac{\pi}{4} \times (\text{OD}_{\text{fiber}}^2 - \text{ID}_{\text{fiber}}^2); \quad [\text{m}^3] \] Volume of each fiber

\[ V_{\text{memb SU}} = \frac{31.6}{A_{\text{fiber}}} \times V_{\text{fiber}}; \quad [\text{m}^3] \] Volume of membrane material of each small unit

\[ \text{density}_{\text{memb}} = 1.78 \times 10^3; \quad [\text{kg/m}^3] \] Density of membrane material

\[ M_{\text{memb SU}} = \text{density}_{\text{memb}} \times V_{\text{memb SU}}; \quad [\text{kg}] \] Mass of membrane material per small unit

\[ M_{\text{memb tot}} = N_{\text{SU,PLU}} \times N_{\text{LU,pt}} \times N_{\text{train}} \times M_{\text{memb SU}}; \quad [\text{kg}] \] Total Mass of membrane material

---

**Listing B.10: Permeate Pumping (Submerged)**

```matlab
function [Q_PERM_mgd, NP_PERM, P_input_PERM, M_SS_PERM] = Permeate_Pumping_Submerged(Q_mgd, N_train, D_train, L_train, ...
W_N_trains, TMP)

% Input:
% Influent flow rate, Q_mgd [mgd]
% Number of trains, N_train
% Depth of each train, D_train [ft]
% Length of each train, L_train [ft]
% Width of N trains, W_N_trains [ft]
% Transmembrane pressure, TMP [psi]

Q_PERM_mgd = Q_mgd; % [mgd] Total permeate pumping flow rate
NP_PERM = N_train; % # of permeate pumps in duty (assume 1 pump per train)

% --> Static head
H_ss_PERM = 9 + 7/12 - 18/12; % [ft] Suction Static Head
\quad % 9'-7" is the water level in membrane trains
\quad % 18" is the distance from C/L of the pump to the ground
H_ds_PERM = 30/12/2 + 6 + D_train - 18/12; % [ft]
H_ts_PERM = H_ds_PERM - H_ss_PERM; % [ft] Total Static Head
```
Listing B.11: Permeate Pumping (Cross-Flow)

function [Q_PERM_mgd, NP_PERM, P_input_PERM, M_SS_PERM] = Permeate_Pumping_Cross_Flow(Q_mgd, N_LU, TMP)

% Permeate Pumping
Q_PERM_mgd = Q_mgd; % [mgd] total permeate flow rate
NP_PERM = N_LU; % # of permeate pumps in duty (assume 1 pump per ... membrane unit)

% --> Static head
H_ss_PERM = 0; % [ft] Suction Static Head
H_ds_PERM = 13; % [ft] Discharge Static Head (based on a unit height of ... 4.6 m)
H_ts_PERM = H_ds_PERM - H_ss_PERM; % [ft] Total Static Head

% --> Pressure head
H_p_PERM = TMP * 2.3106; % [ft] TMP in water head

% --> Suction side
% Suction pipe (permeate headers)
L_s_PERM = L_train + 4.5/17*(75 - 22); % [ft] Length of permeate header per train

% --> Discharge side
% Discharge pipe (Permeate collector)
L_d_PERM = W*N_trains; % [ft] length of permeate collector

[P_input_PERM, M_SS_PERM] = Pumping(Q_PERM_mgd, NP_PERM, H_ts_PERM, ...
L_s_PERM, L_d_PERM, H_p_PERM);
end
% --> Pressure head
Hp_PERM = TMP * 2.3106; % [ft] TMP in water head

% --> Suction side
% Suction pipe (permeate headers)
L_s_PERM = 20; % [ft] length of permeate header of each module (based ...
on a 30-module unit length 6 m)

% --> Discharge side
% Discharge pipe (Permeate collector)
L_d_PERM = 10 * N_LU; % [ft] length of permeate collector (based on a ...30-module unit width 1.6 m and space between modules)

[P_input_PERM, M_SS_PERM] = Pumping(Q_PERM_mgd, NP_PERM, H_ts_PERM, ...
L_s_PERM, L_d_PERM, H_p_PERM);
end

Listing B.12: Gas Sparging (Submerged)

function [Q_gas_cfm, NB, P_input_blower, M_SS_gh, M_SS_gsm, OD_gh, ...
OD_gsm] = Gas_Sparging_Submerged(N_train, N_cassette_pt, ...
A_cassette, SGD, L_train, W_PB, L_BB, freq)
% Input:
% Number of trains, N_train
% Number cassettes per train, N_cassette_pt
% Surface area of each cassette, A_cassette [ft^3]
% Specific gas demand, SGD [Nm^3 gas/m^2 membrane area-h]
% Length of each train, L_train [ft]
% Width of pump building, W_PB [ft]
% Length of Blower building, L_BB [ft]
% Sparging frequency, freq

NB = ceil(N_train / 2); % # of blowers in duty (assume 1 blowers per 2 ...trains)
\% Air Header
\[ L_{gh} = L_{train}; \text{ \{ft\} single length of air header} \]

\% Air Supply Manifold
\[ L_{gsm} = (21 + 2) \ast N_{train} - (N_{train} - 1) \ast 1 + W_{PB} + L_{BB}; \text{ \{ft\} length ... of air supply manifold} \]

\% Gas Requirement
\[ Q_{gas_{cfm pt}} = (SGD \ast 3.2808399/60) \ast N_{cassette_{pt}} \ast A_{cassette}; \text{ \{...\} \{ft^3/min\} gas requirement per train} \]
\[ Q_{gas_{cfm}} = Q_{gas_{cfm_{pt}}} \ast N_{train}; \text{ \{ft^3/min\} total gas requirement} \]
\[ Q_{gas_{cfs_{pt}}} = Q_{gas_{cfm_{pt}}} \ast 60; \text{ \{ft^3/s\} gas requirement per train} \]
\[ Q_{gas_{cfs}} = Q_{gas_{cfs_{pt}}} \ast N_{train}; \text{ \{ft^3/s\} total gas requirement} \]

\% Air Header
\[ VEL_{gh} = 2 \ast 10^5; \text{ \{ft/s\} air velocity in air headers ...} \]
\[ \text{!!!!!!assumption!!!!!!!} \]
\[ [OD_{gh}, t_{gh}, ID_{gh}] = \text{pipe}(Q_{gas_{cfs_{pt}}}, VEL_{gh}); \]

\% Air Supply Manifold
\[ VEL_{gsm} = 2 \ast 10^5; \text{ \{ft/s\} air velocity in air supply manifold ...} \]
\[ \text{!!!!!!assumption!!!!!!!} \]
\[ [OD_{gsm}, t_{gsm}, ID_{gsm}] = \text{pipe}(Q_{gas_{cfs}}, VEL_{gsm}); \]

\% Pipe material (assume stainless steel, density = 0.29 lbs/in^3)
\[ V_{gh} = N_{train} \ast \pi/4 \ast ((OD_{gh})^2 - (ID_{gh})^2) \ast (L_{gh} \ast 12); \]
\[ V_{gsm} = \pi/4 \ast ((OD_{gsm})^2 - (ID_{gsm})^2) \ast (L_{gsm} \ast 12); \]
\[ M_{SS_{gh}} = 0.29 \ast V_{gh} \ast 0.453592; \text{ \{kg\} mass of stainless steel} \]
\[ M_{SS_{gsm}} = 0.29 \ast V_{gsm} \ast 0.453592; \text{ \{kg\} mass of stainless steel} \]
\[ M_{SS_{gas}} = M_{SS_{gh}} + M_{SS_{gsm}}; \text{ \{kg\} mass of stainless steel} \]

\text{TDH_{blower_{psig}}} = 6; \text{ \{psig\} estimated TDH (estimation based on ... Hazen&Sawyer spreadsheet)} \]
\[ \text{Eff_{blower}} = 0.7; \text{ \{...\} blower efficiency} \]

13
14 \% Air Header
15 \[ L_{gh} = L_{train}; \text{ \{ft\} single length of air header} \]
16
17 \% Air Supply Manifold
18 \[ L_{gsm} = (21 + 2) \ast N_{train} - (N_{train} - 1) \ast 1 + W_{PB} + L_{BB}; \text{ \{ft\} length ... of air supply manifold} \]
19
20 \% Gas Requirement
21 \[ Q_{gas_{cfm pt}} = (SGD \ast 3.2808399/60) \ast N_{cassette_{pt}} \ast A_{cassette}; \text{ \{...\} \{ft^3/min\} gas requirement per train} \]
22 \[ Q_{gas_{cfm}} = Q_{gas_{cfm_{pt}}} \ast N_{train}; \text{ \{ft^3/min\} total gas requirement} \]
23 \[ Q_{gas_{cfs_{pt}}} = Q_{gas_{cfm_{pt}}} \ast 60; \text{ \{ft^3/s\} gas requirement per train} \]
24 \[ Q_{gas_{cfs}} = Q_{gas_{cfs_{pt}}} \ast N_{train}; \text{ \{ft^3/s\} total gas requirement} \]
25
26 \% Air Header
27 \[ VEL_{gh} = 2 \ast 10^5; \text{ \{ft/s\} air velocity in air headers ...} \]
\[ \text{!!!!!!assumption!!!!!!!} \]
28 \[ [OD_{gh}, t_{gh}, ID_{gh}] = \text{pipe}(Q_{gas_{cfs_{pt}}}, VEL_{gh}); \]
29
30 \% Air Supply Manifold
31 \[ VEL_{gsm} = 2 \ast 10^5; \text{ \{ft/s\} air velocity in air supply manifold ...} \]
\[ \text{!!!!!!assumption!!!!!!!} \]
32 \[ [OD_{gsm}, t_{gsm}, ID_{gsm}] = \text{pipe}(Q_{gas_{cfs}}, VEL_{gsm}); \]
33
34 \% Pipe material (assume stainless steel, density = 0.29 lbs/in^3)
35 \[ V_{gh} = N_{train} \ast \pi/4 \ast ((OD_{gh})^2 - (ID_{gh})^2) \ast (L_{gh} \ast 12); \]
36 \[ V_{gsm} = \pi/4 \ast ((OD_{gsm})^2 - (ID_{gsm})^2) \ast (L_{gsm} \ast 12); \]
37 \[ M_{SS_{gh}} = 0.29 \ast V_{gh} \ast 0.453592; \text{ \{kg\} mass of stainless steel} \]
38 \[ M_{SS_{gsm}} = 0.29 \ast V_{gsm} \ast 0.453592; \text{ \{kg\} mass of stainless steel} \]
39 \[ M_{SS_{gas}} = M_{SS_{gh}} + M_{SS_{gsm}}; \text{ \{kg\} mass of stainless steel} \]
40
41 \text{TDH_{blower_{psig}}} = 6; \text{ \{psig\} estimated TDH (estimation based on ... Hazen&Sawyer spreadsheet)} \]
42 \[ \text{Eff_{blower}} = 0.7; \text{ \{...\} blower efficiency} \]
Eff\textsubscript{motor,BL} = 0.7; \text{\% motor efficiency}

\text{BHP\_blower\textsubscript{tot}} = (Q\_gas\_cfm \times 0.23) \times \(((14.7 + \ldots \quad 45
TDH\_blower\_psig)/(14.7)^{0.283} - 1.0) / \text{Eff\_blower};

\text{P\_input\_blower} = \text{BHP\_blower\textsubscript{tot}} \times 0.746 / \text{Eff\textsubscript{motor,BL}} \times \text{freq}; \text{\% [Kw] ...}

\text{Power input to motor}

\text{end}

\text{Listing B.13: Chemical Cleaning}

\begin{verbatim}
function [M\textsubscript{NaOCl\_kg}, Q\textsubscript{NaOCl\_weekly}, M\textsubscript{CA\_kg}, Q\textsubscript{CA\_weekly}] = ... 
\text{Chemical\_Cleaning (Q\_mgd, Year)}
\text{\% Input:}
\text{\% Inflent water flow rate, Q\_mgd [mgd]}
\text{\% Operation time, Year [years]}
\text{\% --\to Clean In Place (CIP): Weekly cleaning with 500 mg/L NaOCl and ...}
\text{2000 mg/L citric acid}
\text{\% --\to Clean Out of Place (COP): Biannual cleaning with \? mg/L NaOCl and ...}
\text{\% mg/L citric acid}
\text{\% Sodium Hypochlorite (12.5\% solution, 15\% by volume)}
\text{Dose\_NaOCl} = 2200; \text{\% [gal/yr/mgd] NaOCl Usage Rate}
\text{Q\textsubscript{NaOCl\_annual}} = \text{Dose\_NaOCl} \times Q\_mgd; \text{\% [gal/yr] NaOCl annual flow rate}
\text{Q\textsubscript{NaOCl\_weekly}} = Q\textsubscript{NaOCl\_annual} / 52; \text{\% [gal/week] NaOCl weekly flow rate}
\text{M\textsubscript{NaOCl\_kg}} = Q\textsubscript{NaOCl\_annual} \times 3.78541 \times (12.5/15) \times \text{Year}; \text{\% [kg] Mass ...}
\text{of NaClO consumption over N years}
\text{\% 12.5\% by weight = 12.5 g solute/100 mL solution}
\text{\% 15\% by volume = 15 mL solute/100 mL solution}
\text{\% \(12.5 \text{ kg/15 L}\)}
\text{\% 1 gal = 3.78541 L}
\text{\% Citric Acid (100\% solution, 13.8 lb/gal)}
\text{Dose\_CA} = 600; \text{\% [gal/yr/mgd] Citric acid Usage Rate}
\text{Q\_CA\_annual} = \text{Dose\_CA} \times Q\_mgd; \text{\% [gal/yr] Citric acid annual flow rate}
\end{verbatim}
Listing B.14: Chemical Pumping

```
function [Q_CHEM_mgd, NP_CHEM, P_input_CHEM, M_SS_CHEM, M_HDPE_CHEM_kg] ...
    = Chemical_Pumping(Q_CHEM_weekly)

% Input:
% Weekly flow rate of chemical solution, Q_CHEM_weekly [gal/week]

% Chemical container (assume cubic in shape, HDPE in material)
V_CHEM = 2 * Q_CHEM_weekly * 0.00378541; % [m^3] Volume of container holding 2 weeks of chemicals
% 1 gal = 0.00378541 m^3
t_container = 0.003; % [m] Thickness of container
V_HDPE = t_container * (V_CHEM^(1/3))^2 * 6; % [m^3] Volume of container material
Ro_HDPE = 950; % [kg/m^3]
M_HDPE_CHEM_kg = Ro_HDPE * V_HDPE; % [kg]

% Chemical pumping
Q_CHEM_mgd = Q_CHEM_weekly / 10^6 / 7; % [mgd] Total permeate pumping flow rate
NP_CHEM = 1; % # of permeate pumps in duty

% --> Static head
H_ss_CHEM = V_CHEM^(1/3) * 3.28084; % [ft] Suction Static Head % 3.28084 ft = 1 m
H_ds_CHEM = 9 + 7/12 - 18/12; % [ft] Suction Static Head
    % 9'-7" is the water level in membrane trains
    % 18" is the distance from C/L of the pump to the ground
```
H_{ts\_CHEM} = H_{ds\_CHEM} - H_{ss\_CHEM}; \ [ft] \ Total \ Static \ Head

% --> Pressure head
H_{p\_CHEM} = 0; \ [ft]

% --> Suction side
% Suction pipe (permeate headers)
L_{s\_CHEM} = 0; \ [ft] \ Length \ of \ permeate \ header \ per \ train

% --> Discharge side
% Discharge pipe (Permeate collector)
L_{d\_CHEM} = 30; \ [ft] \ length \ of \ permeate \ collector

[P\_input\_CHEM, M\_SS\_CHEM] = Pumping(Q_{CHEM}\_mgd, N_P\_CHEM, H_{ts\_CHEM}, ... 
L_{s\_CHEM}, L_{d\_CHEM}, H_{p\_CHEM});

end
C.1 Submerged AnMBR with CSTR Reactors

C.1.1 System Configuration

In this configuration, influent wastewater first enters an concrete channel called influent distribution channel, and then is distributed into multiple membrane trains (A membrane train is a concrete channel parallel to water flow direction with a row of membrane modules submerged in it). Membrane filtrations is driven by vacuum pressure, which is provided by permeate pumps. Effluent leaves the reactor through a permeate collector. Membrane fouling is controlled by biogas sparging, which is provided by blowers. A wet well is used to collect mixed liquor, which is recirculated back to the influent distribution channel. The submerged membrane modules selected for this configuration are flat sheet membranes.

C.1.2 Term Definitions and Design Equations

Membrane Train

Each membrane train contains 2 rows of membrane cassettes. The width of each train \( W_{\text{train}} \) is assumed to be 20 ft, and the depth of each train \( D_{\text{train}} \) is assumed to be 12 ft. The cross-section of a single membrane train is shown in the Fig. C.1

The nominal membrane surface area of each membrane module \( A_{\text{module}} \) is assumed to be 340 \( ft^2 \) (based on GE ZeeWeed* 500D Module). Assume each membrane cassette contains 48 modules.

\[
A_{\text{cassette}} = 48 \times A_{\text{module}} \tag{C.1}
\]
So, the volume of each train can be calculated by Eq.C.2, and hydraulic retention time (HRT) can be determined by Eq.C.3, where $N_{train}$ is the total number of membrane trains designed.

\[ V_{train} = \frac{Q}{\text{Length} \times \text{Width} \times \text{Depth}} \]  \hspace{1cm} (C.2)

\[ HRT = \frac{V_{train}}{Q \times N_{train}} \]  \hspace{1cm} (C.3)
The amount of concrete required for infrastructure is estimated based on the detailed design. Minimum concrete wall thickness \((t_{wall})\) is assumed to be 12 feet, and 1 inch is added to wall thickness for every foot of depth over 12 feet. Concrete slab thickness \((t_{slab})\) is assumed to be 2 inches greater than wall thickness. Fig.C.3 shows the concrete composition, which can be divided into three portions: Portion I (shown in green), Portion II (shown in blue), and Portion III (shown in cyan). Portion I is called membrane distribution channel, which is used to distribute the influent into multiple membrane trains. The width of distribution channel \((W_{\text{dist}})\) is assumed to be 4.5 ft. For a N-train membrane tank, there are \((N - 1)\) shared walls. So, the total width of N trains \((W_{N_{\text{trains}}})\) can be calculated by Eq.C.4. Portion II is composed of multiple membrane trains, which are separated by concrete walls. Portion III consists of the membrane effluent channel (assume 5 foot wide) and the concrete structure that contains the piping and pumping equipment.

\[
W_{N_{\text{trains}}} = (W_{\text{train}} + 2t_{\text{wall}})N_{\text{trains}} - t_{\text{wall}}(N_{\text{trains}} - 1) \tag{C.4}
\]

Wall concrete and slab concrete are estimated separately. The volume of wall concrete needed to build portion I can be calculated by Eq.C.5, and the volume of slab concrete needed to build portion I can be calculated by Eq.C.6.

\[
V_{wall, I} = D_{\text{train}}t_{\text{wall}}(2W_{N_{\text{trains}}} + 2W_{\text{dist}}) \tag{C.5}
\]
The volume of wall concrete needed to build portion II can be calculated by Eq.C.7, and the volume of slab concrete needed to build portion II can be calculated by Eq.C.8.

\[ V_{\text{wall, II}} = D_{\text{train}} t_{\text{wall}} (N_{\text{train}} + 1) L_{\text{train}} \] (C.7)

\[ V_{\text{slab, II}} = N_{\text{train}} (D_{\text{train}} + W_{\text{train}}) t_{\text{slab}} L_{\text{train}} \] (C.8)

The volume of wall concrete needed to build portion III can be calculated by Eq.C.9, and the volume of slab concrete needed to build portion III can be calculated by Eq.C.10.

\[ V_{\text{wall, III}} = D_{\text{train}} t_{\text{wall}} (2W_{\text{Ntrains}} + 2W_{\text{eff}}) + D_{\text{train}} t_{\text{wall}} (2W_{\text{Ntrains}} + 2W_{\text{PB}} + 2W_{\text{BB}}) \] (C.9)

\[ V_{\text{slab, III}} = W_{\text{Ntrains}} (W_{\text{eff}} + 2t_{\text{wall}}) t_{\text{slab}} + W_{\text{Ntrains}} (W_{\text{PB}} + t_{\text{wall}} + W_{\text{BB}}) t_{\text{slab}} \] (C.10)

Wet Well is designed to store mixed liquor that needs to be recycled. Depth of Wet Well \((D_{\text{well}})\) is assumed to be 12 ft, width \((W_{\text{well}})\) is assumed to be 8 ft, and length \((L_{\text{well}})\) is assumed to be 8 ft. The volume of wall concrete needed to build wet well can be calculated by Eq.C.11, and the volume of slab concrete needed to build wet well can be calculated by Eq.C.12.

\[ V_{\text{wall, well}} = (D_{\text{well}} - t_{\text{slab}}) [L_{\text{well}} t_{\text{wall}} + (W_{\text{well}} - 2t_{\text{wall}}) t_{\text{wall}}] \] (C.11)

\[ V_{\text{slab, well}} = t_{\text{slab}} L_{\text{well}} W_{\text{well}} \] (C.12)
C.1.3 Pumping

As shown in Fig.C.4, one pump per train is required for permeate pumping, and one pump in total is used for recirculation pumping.

![Figure C.4: Schematic for submerged AnMBR with CSTR reactors](image)

C.1.4 Piping

The piping required for AnMBR of this configuration includes a gas supply manifold, gas headers, a permeate collector, and permeate headers (shown in Fig.C.5).

C.1.5 Membrane Modules

GE ZeeWeed*500D membrane modules are assumed to be used for AnMBRs with the submerged configurations. ZeeWeed*500D uses PVDF hollow-fiber membrane.
C.2 Cross-flow AnMBR with Anaerobic Filter

C.2.1 System Configuration

In this configuration, influent wastewater is pumped into an up-flow anaerobic filter, and then enters membrane filtration.

C.2.2 Pumping

The pumping required for this AnMBR includes influent lift pumping, permeate pumping, recirculation pumping for anaerobic filters, and membrane retentate pumping, which are shown in Fig.C.8.
C.2.3 Membrane Modules

Membrane modules utilized for AnMBRs of external cross-flow configuration is tubular membrane modules (assume Norit X-flow model AQFMBR). Each membrane module has a surface area ($A_{\text{module}}$) of 32 m$^2$, and membrane unit contains 30 membrane modules (shown in Fig.C.7). The number of membrane modules ($N_{\text{module}}$) required is based on an design flow rate ($Q$) and a operating flux ($J$), and is calculated by Eq.C.13.

$$N_{\text{module}} = \frac{Q}{J A_{\text{module}}} \tag{C.13}$$

Retentate flow rate ($Q_{\text{retentate}}$) is quantified based on an assumed the cross-flow velocity ($V_{x\text{flow}}$) (assume 1 m/s), and is calculated by Eq.C.14, where 29.3 is a factor provided in the spec sheet of ”Norit X-flow model AQFMBR”.

$$Q_{\text{retentate}} = N_{\text{module}} \times 29.3 \times V_{x\text{flow}} \tag{C.14}$$
Figure C.7: External Tubular Membrane Unit

Figure C.8: Schematic of external cross-flow AnMBRs with anaerobic filter