DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MODELLING OF MEMBRANE BIOREACTOR SYSTEMS

by
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July, 2013
İZMİR

MODELLING OF MEMBRANE BIOREACTOR SYSTEMS

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"MODELLING OF MEMBRANE BIOREACTOR SYSTEMS"** completed by **FERİT ÇAĞLAR** under supervision of **PROF. DR. NURDAN BÜYÜKKAMACI** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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MODELLING OF MEMBRANE BIOREACTOR SYSTEMS

ABSTRACT

As a result of the ever-increasing the world population, declining fresh water source has given rise to the need for conservation management of wastewater more efficiently. Accordingly, it has increased the need of wastewater reuse applications. Especially due to the benefits of the low space requirement and nutrient removal, the important of the membrane bioreactor (MBR) has emerged. Obtaining better quality effluent with the expansion of membrane bioreactor, wastewater can be reused and accordingly, fresh water sources can be protected more effectively. It is obvious that the increase in the efficiency of wastewater treatment with the use of membranes in the biological processes provides an important contribution to the protection of water sources.

To achieve targeted results with the use of membrane bioreactor processes, system design and determination of the optimum operating parameters have a great importance. For this reason, the issues that must be considered for membrane bioreactor design are investigated and the design phases described in this study. The bioreactor design was made according to the ATV-DVWK-A 131 E design criteria for the municipal wastewater. The required bioreactor volume and oxygen demand were calculated according to the different MLSS, SRT and Recycle Ratio and the results were compared for integrated and separated MBR system. Consequently, examining the effects of the some important parameters on the operational of membrane bioreactor system were tried to determine.

Keywords: Membrane bioreactor (MBR), desig, wastewater treatment, ATV-DVWK-A 131 E.

MEMBRAN BİYOREAKTÖR SİSTEMLERİN MODELLENMESİ

ÖZ

Giderek artan dünya nüfusunun bir sonucu olarak azalan temiz su kaynaklarının korunması, atıksuların daha etkin bir şekilde yönetilmesi ihtiyacını doğurmuştur. Buna bağlı olarak arıtılmış atıksuların yeniden kullanım ihtiyacı da artmıştır. Düşük alan gereksinimi ve nütrient giderimi avantajlarından ötürü de membran biyoreaktörlerin (MBR) önemi ortaya çıkmıştır. Membran biyoreaktörlerin yaygınlaşması ile daha iyi kalitede çıkış suyu elde edilerek, atıksu geri kazanımı mümkün olabilmekte ve buna bağlı olarak temiz su kaynakları daha etkin bir şekilde korunabilmektedir. Böylelikle, membranların biyolojik arıtma prosesleri olarak kullanımı ile arıtma verimliliğinin artmasının yanı sıra su kaynaklarının korunmasına da önemli katkılar sağlayacağı açıktır.

Membranlı biyolojik arıtma proseslerinin kullanılması ile, hedeflenen sonuca ulaşmak için sistem tasarımı ve optimum işletme parametrelerinin belirlenmesi de büyük bir önem taşımaktadır. Bu nedenle tez çalışmasında, membran biyoreaktör tasarımında dikkat edilmesi gereken hususlar araştırılmış olup, tasarım aşamaları anlatılmıştır. Sistem tasarımında kentsel nitelikli bir atıksu kaynağı seçilmiş olup, biyoreaktör tasarımı ATV-DVWK-A 131 E tasarım kriterine göre yapılmıştır. Gerekli biyoreaktör hacmi ve oksijen ihtiyacı, farklı MLSS, SRT ve geri devir oranlarına göre yapılarak sonuçlar birleşik ve ayrık MBR sistemleri için karşılaştırılmıştır. Böylelikle MBR sisteminin işletilmesinde bazı önemli parametrelerin etkileri incelenerek optimum tasarım parametreleri belirlenmeye çalışılmıştır.

Anahtar kelimeler: Membran biyoreaktör (MBR), tasarım, atıksu arıtımı, ATV-DVWK-A 131 E.

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CHAPTER ONE
INTRODUCTION

1.1 Introduction

There is growing concern about the sustainable development and different sensible solution to protect the natural sources worldwide. The one of the most essential ways to protect fresh water resources is to manage wastewater properly. In order to enhance wastewater treatment plant effluent quality, several types of treatment units have been examined and operated so far. By combining aerobic biological treatment with membrane system, the membrane bioreactor (MBR) system significantly improve effluent quality. The use of MBR in municipal wastewater treatment has grown widely because of the more stringent effluent water quality requirements. MBR systems have several advantages, such as excellent effluent quality, disinfection capacity, less footprint requirement, higher volumetric loading, less sludge production, lower operator involvement, modular expansion characteristics, etc., comparing to conventional biological treatment systems (Judd, 2006; EPA, 2007; Till & Malia, 2001).

In MBR systems, membrane is used for solid/liquid separation instead of secondary clarifiers in conventional activated sludge systems. MBR systems enable perfect physical retention of bacterial flocks and virtually all suspended solids within the bioreactor by using microfiltration or ultrafiltration membrane with a maximum nominal pore size of 0.4 µm. Compared to conventional processes, the quality of solid separation is not depending on the MLSS (Mixed Liquor Suspended Solids) concentration or the settling characteristic. Due to the advantage provided by, MBR has now seen as one of the most effective methods for the treatment of industrial wastewater and municipal wastewater where a small footprint, water reuse or stringent discharge standards are required.

MBR technology was first introduced by the late of 1960s and has made many stages in the process of historical development. One of the best developments emerged at the end of 1980s by using the submerged membrane bioreactor and found a chance to practice into larger plants after the mid 90s (Smith, Gregorio & Talcott, 1969; Yamamoto, Hiasa, Mahmood & Matsuo, 1989; Sutton, 2006). And then the application of MBR systems has extended widely due to its benefits, especially in the last 10 years. In addition to this, scientific researches are improving quickly around the world. Basically, the researcher focused on fouling occurred on the membrane surface and energy consumption. These are the most important factors restricting the development of the MBR systems. Because, filtration performance can be limited by membrane fouling and the aim of most studies about MBR process is to inhibit or to limit fouling in order to upgrade system performances (Chang, Fane & Vigneswaran, 2002). Several researchers have been working on to reduce operation cost via reducing power requirements for aeration and cleaning (Mansell, Peterson, Tang, Horvath & Stahl, 2006). One of the issues researchers are studying in recent years is modeling and simulation of MBR systems, especially for fouling membrane (Aileen & Albert 2007; Liang, Song & Tao, 2006).

The basic principle of the modeling and simulation used in the activated sludge process, constitute knowledge about behavior systems and to create a better operational conditions. Process modeling helps to understand the relationship between parameters, to predict to effluent quality, and to improve processing efficiency.

1.2 Aim and Scope of the Thesis

The aim of this thesis is a discussion and application of biological modeling as a means to help evaluate the design criteria. Knowledge presented in this thesis should help MBR system operators. The thesis is mainly composed of 5 Chapters, including discussion and conclusion. In the Chapter 1, the past and future significance of membrane bioreactor system is described and the aspect of this thesis explained briefly. The process configuration, variable operational conditions for membrane bioreactor systems are given in Chapter 2. Also, the reason of the fouling occurred on the membrane surface and how fouling can be minimized as well as cleaning procedure described in this chapter. Moreover, MBR system is compared with conventional activated sludge process. In Chapter 3, some modeling & simulation programs used for the activated sludge process design and optimization are introduced. In Chapter 4, the two-part design model was adopted. At first part, the required membrane surface is determined and the dimensions of the MBR tank are calculated. At the second part, the bioreactor design is carried out according to ATV A131E and depending on the different design parameters; the obtained results are given and discussed in Chapter 5.

CHAPTER TWO
MEMBRANE BIOREACTOR TECHNOLOGY

2.1 Membrane Bioreactor

Recently developed and one of the most hopeful technology is Membrane Bioreactor (MBR) has became more and more used in recent years to overcome the limitation of conventional systems. These systems have the advantage of combining a suspended growth biological biomass with solids removal via filtration. Nevertheless, the membrane activated sludge process is relatively new technologies, which still demand considerable research and development, especially in the fields of wastewater pre-treatment, chemical and mechanical membrane cleaning, fouling and scaling. Furthermore, a few years ago there were almost no MBR system in operation, this technology was generally unknown in the marketplace and the main reason why the technology was not being utilized were:

- Untested, complex and small scale
- High cost
- High operator skill required
- Unknown maintenance and labor requirement
- Membrane failure rate known
- No requirement for high effluent quality

“The membrane filtration system in effect can replace secondary clarifier and sand filters in a typical activated sludge treatment system” (http://tech-action.org). Membrane filtration allows a higher biomass concentration to be maintained, thereby allowing smaller bioreactors to be used (EPA, 2007).

The Membrane Bioreactor System (MBR) consists of an activated sludge tank and a solid-liquid separation unit including membrane module. The process of the conventional activated sludge (CAS) system and the membrane bioreactor (MBR) is shown in Figure 2.1. Unlike the conventional activated sludge system, the activated sludge is separated via membrane filtration in membrane bioreactor systems.

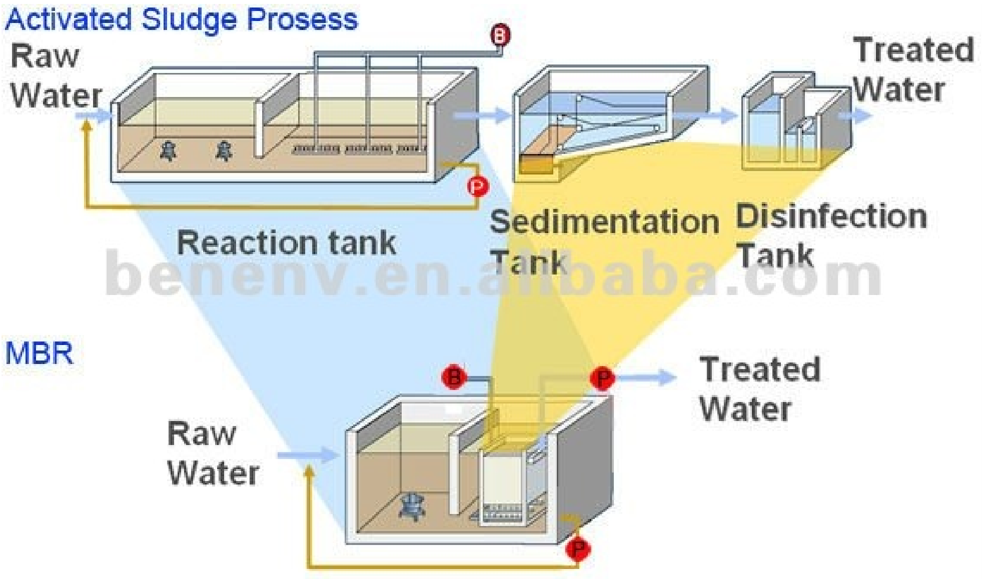


Figure 2.1 Conventional activated sludge system and MBR system (Image from http://benenv.en.alibaba.com)

By this time, MBR systems have mainly been used for smaller application due to the high investment and operating cost. Today however, they are receiving increased use in larger systems. Furthermore, MBR systems are also well-suited for some industrial applications.

2.2 History Development of Membrane Bioreactor Technology

"MBR technology was first introduced by the late 1960s. This research carried out in the Department of Environmental Engineering, as soon as commercial ultrafiltration (UF) and microfiltration (MF) membranes were available. The aim of this research was to develop a new and efficient biological separation procedure for the treatment of municipal and industrial wastewater" (Stiefel & Washington, 1966; Hardt, Clesceri, Nemerow & Washington, 1970; Smith et al., 1969).

The original process was developed by Dorr Oliver Inc. that is one of the members of the above research group and combined an activated sludge bioreactor with a cross flow membrane filtration. Firstly, the pore sizes ranging from 0.003 to 0.01 µm polymeric flat sheet membranes used in this process. Although the idea of replacing the settling tank of the conventional activated sludge process was attractive, it was difficult to justify the use of such a process because of the high cost of membranes and the potential rapid loss of performance due to membrane fouling. As a result, the first generation MBR system could not find a chance to practice at wide range applications because of uneconomically.

In 1969, the oxygen transfer and consumption in an activated sludge process with wide range of MLSS concentrations (12,500 - 37,500 mg/L) was considered by Stiefel et al. It was observed that while the MLSS concentration increased the respiration rate of the activated sludge decreased. This situation could be due to lack of oxygen in the high MLSS concentration.

In 1970, a research study was carried out by Hard et al. by using ultrafiltration membranes as a separation method. A success was acquired at a high value of 25 g/L MLSS concentration. On the other hand, the flux rate was very low (6 - 11 L/m^2.h).

One of the best developments in the historical process of MBR technology was investigated by Yamamoto et al. at the end of the 1989s by using the submerged membrane bioreactor. By that time, the side stream MBR were designed as a separation method of the activated sludge placed external to the biological reactor and it was depended on the high Trans Membrane Pressure (TMP). With the development of submerged type membrane system, the system has been most preferred, in particular for the municipal wastewater treatment. Also, to ensure a homogeneous mixing of the activated sludge and to control the clogging of the membrane surface, the coarse bubble aeration system was used. With a pore size 0.1 µm submerged type membranes were used and the investigations were performed with wide range of MLSS concentrations, also the flux value was kept 10 L/m^2.h as a constant value. As a result, because of the oxygen transfer efficiency decreased at a very high MLSS concentration (over the 40 g/L MLSS), under the 30 g/L MLSS concentration was recommended to maintain a stable operation.

Consequently, the historical development of MBR technology was continued and found a chance to practice into larger plants after the mid 90s. Thus, the developments gained a significant momentum and more reasonable operating parameters were determined depending on the wastewater characterization. While early MBR systems were operated at SRT (solid retention time) as high as 100 days with MLSS (mixed liquid suspended solids) up to 30 g/L, the recent trend is to apply lower SRT around 10–20 days, resulting in more manageable MLSS levels around 10-15 g/L. Thanks to these new operating conditions, the oxygen transfer and the pumping cost in the MBR have tended to decrease and overall maintenance has been simplified. There is now a range of MBR systems commercially available, most of which use submerged membranes although some external modules are available. Typical hydraulic retention times (HRT) range between 3 and 10 hours. In terms of membrane configurations, mainly hollow fiber and flat sheet membranes are applied for MBR applications.

2.3 Advantage of Membrane Bioreactor Technologies

MBR technology is basically emerged due to the limitation of the conventional systems. Specifically, MBR systems can be operated at higher volumetric loading rates which result in lower hydraulic retention times. The low retention times mean that less space is required compared to a conventional system.

MBRs have often been operated with longer sludge retention time (SRT), which results in lower sludge production. The membrane provides usually 30-60 days SRT, which can greatly enhance the biological degradation of influent organics (Coppen, 2004). However, this is not a requirement, and more conventional SRT have been used (Crawford, Thompson, Lozier, Daigger & Fleischer, 2000). Due to the high sludge age, the production of the sludge is 35% less than conventional system, sludge handling and disposal cost are lower and also the sludge is highly stabilized (Till et. al., 2001). Higher operating cost due to the energy requirement are generally balanced by the lower cost for the sludge disposal with running at longer sludge residence times and with membrane thickening/dewatering of waste sludge. A comparison between various activated sludge processes in terms of sludge productions are given in Table 2.1.

Table 2.1 Sludge production between the various activated sludge process (Mayhew, Stephenson, 1997)

Treatment Process	**Sludge Production (kg/kg BOD)**
Submerged Membrane Bioreactor	0.0-0.3
Structured Biological Aerated Filter	0.15-0.25
Trickling Filter	0.3-0.5
Conventional Activated Sludge	0.6
Granular Media Biological Aerated Filter	0.63-1.06

One of the limited problems of the conventional activated sludge is the separation of the sludge from the treated water. As a result of the poor settling of the sludge, filamentous bacteria are formed in the conventional process. For MBR process there is not such a problem due to the solid-liquid separation are provided by the filtration method.

The membrane filtration also has a higher level of treatment efficiency compared to the conventional system, contains low bacteria, suspended solids (SS) and biochemical oxygen demand (BOD). Due to this advantage, the effluent can be used as irrigation water and the higher effluent quality also reduces disinfection requirements. Effluent quality is invariably excellent and generally independent of the influent quality (Till et al., 2001). As shown in Table 2.2, removal of COD, TSS and nitrogen is fairly well; COD and TSS in the effluent are under the discharge limit. Phosphorus is also removed well in the system and the effluent in terms of microbiological quality has consistently met discharge limit. Also compared to conventional activated sludge process, nitrification is more effectively owing to the longer retention of nitrifying bacteria (high sludge age, low food/microorganism ratio) (Galil, Sheindorf, Tenenbaum & Levinsky, 2003).

Table 2.2 Comparison of the effluent quality

Parameter	**Unit**	**Conventional WWTP**	**MBR Plant**
TSS	mg/L	10 - 15	3.0
COD	mg/L	40 - 50	< 30
N_{tot}	mg/L	< 13	< 13
P_{tot}	mg/L	0.8 - 1.0	< 0.3
Microbiological Quality		Hygienic Critical	Bathing Water Quality

Consequently, unlike the conventional system, MBR systems have better effluent quality, smaller space requirements, and ease of automation.

2.4 Disadvantage of Membrane Bioreactor Technologies

The primary disadvantage of MBR systems is investment and operating costs. They are higher than conventional systems for the same throughput conventional system as shown in the Table 2.3. Membrane cleaning, and fouling control and eventual membrane replacement are some of the basic operational costs. Energy costs are also higher due to the air scouring to provide cross flow velocities for filtration. The amount of air needed for the scouring has been stated to be twice that needed to maintain aeration in a conventional activated sludge system.

Table 2.3 Investment and operational cost of MBR

Treatment Step	**Saving Potential**	**Additional Cost**
Mechanical Pretreatment		- Fine screening for safety reasons for the membranes
Biological Pretreatment	3 - 4 times smaller volume of the Biological Reactor (MLSS = 12-15 g/L)	- High energy consumption for scoured air and lower oxygen transfer efficiency
Sludge Separation/Tertiary Treatment	- no secondary sedimentation tank - no tertiary treatment (Sand filtration/Disinfection)	- membrane costs - membrane maintenance

In addition, Hermanowicz et al. specified that "the waste sludge originated from such a system might have a low settling rate, resulting in the need for chemicals to produce biosolids acceptable for disposal and the main reason of the low settling rate in waste sludge is due to the increased filamentous bacteria and amount of colloidal-size particles” (Hermanowicz, Jenkins, Merlo & Trussell, 2006). Chemical addition increases the ability of the sludge settle. Fleischer et al. (2005) have demonstrated that waste sludges originated from MBR systems can be committed using standard technologies which uses for conventional activated sludge processes.

2.5 Membrane Filtration

On a filtration point of view, MBR systems can be defined and classified according to through key points of the filtration process: membrane, filtration mode, module design and filtration process (EUROMBR, 2006).

In wastewater treatment applications, with a maximum nominal pore size of 0.4 µm ultrafiltration or microfiltration membranes made from polymeric organics (PVDF, PE, PES) and assembled into units (modules, cassettes, stacks) are usually used to keep the bacteria within the reactor. The most advisable solution to control fouling and clogging of the membrane surface is *crossflow filtration* that explained as the continuous velocity on the membrane surface. The water passing through the membrane in to a separate channel for recovery is shown in Figure 2.2 and named as permeate.

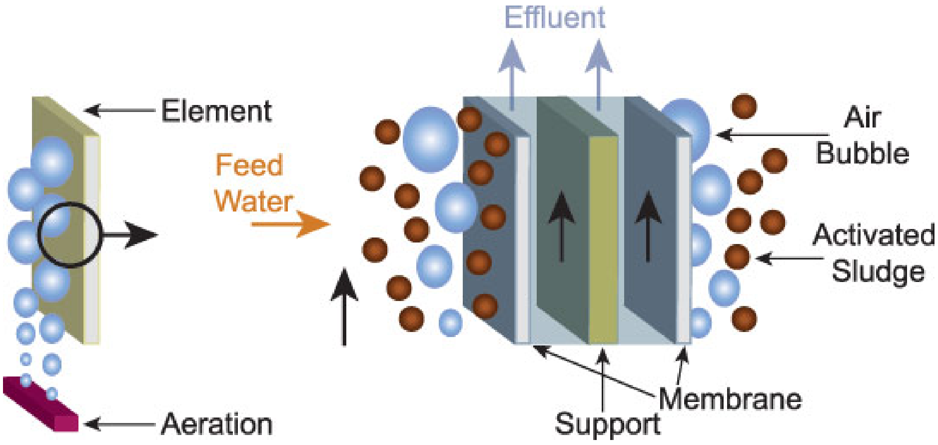
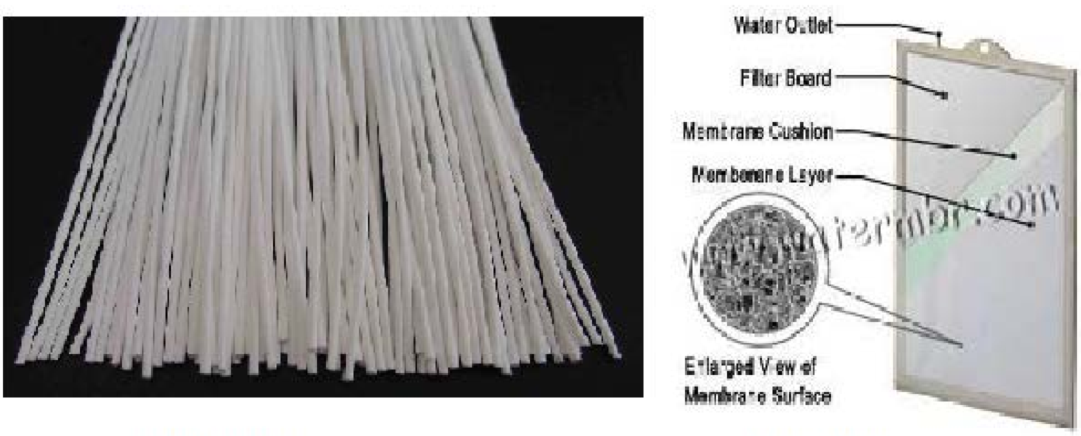


Figure 2.2 Membrane filtration process (Image from http://www.wigen.com)

In membrane bioreactor applications, membranes can be configured in two ways: hollow fibers and flat sheet (Figure 2.3). Both of them can be used as a submerged module for membrane bioreactor system. According to Gupta, Jana, & Majumder, (2008) it is expected that the hollow-fiber submerged configuration would be useful for medium to large size plants for municipal applications. For small to medium size plants, plate and frame technologies would have an advantage, whereas larger applications could be designed with tertiary treatment followed by membrane filtration or ultrafiltration. Some of the MBR manufactured company like SIEMENS/U.S. FILTERS or GE/ZENON use hollow fiber tubular membranes configured in bundles, some of them like TORAY or KUBATO employ membranes in a flat sheet configurations.



a) Hollow Fiber

b)Flat Sheet

Figure 2.3 The appearance of hollow fiber and flat sheet membrane (Image from http://www.watermbr.com)

“For flat sheet module, each membrane is accommodated within a rectangular box which collects permeate. The space between the membrane elements should be at least of 6-7 mm” (Sofia, Ng & Ong, 2004). In MBR system, hollow fiber modules are composed of bundles of fibers with 1.5 to 2.5 mm inner diameter and these type modules are generally carried out in outside/infiltration to avoid fiber clogging (EUROMBR, 2006).

According to location of the membrane module, generally two types MBR configurations are used for filtration (Figure 2.4);

- side-stream (pressurized) membrane filtration
- submerged membrane filtration

Sutton is specified that “The first one is normally referred to as side-stream (pressurized) MBR configuration. The first large full scale MBR system for industrial wastewater treatment was used as a side-stream (pressurized) MBR system. In the beginning of the 1990s, the studies carried out by Japan researchers focused on submerged MBR system where the module directly mounted in to the bioreactors and in the late 1990s, the first large full scale submerged MBR system was installed for treatment of industrial wastewater” (Sutton, 2006).

Membrane filtration is carried out either by side-stream (pressurized) filtration or submerged system directly into the bioreactor. The more common MBR configuration for wastewater treatment is submerged membranes, although a side-stream (pressurized) configuration is also possible. The membrane modules are placed outside of the activated sludge tank for the side-stream (pressurized) configuration, and then the mixture of wastewater in the biological tank pumped through the membrane and the retained concentrate are returned to the activated sludge tank. In the submerged configuration, the filtration is performed within the same activated sludge tank. Therefore, the retained concentrate is not necessary.

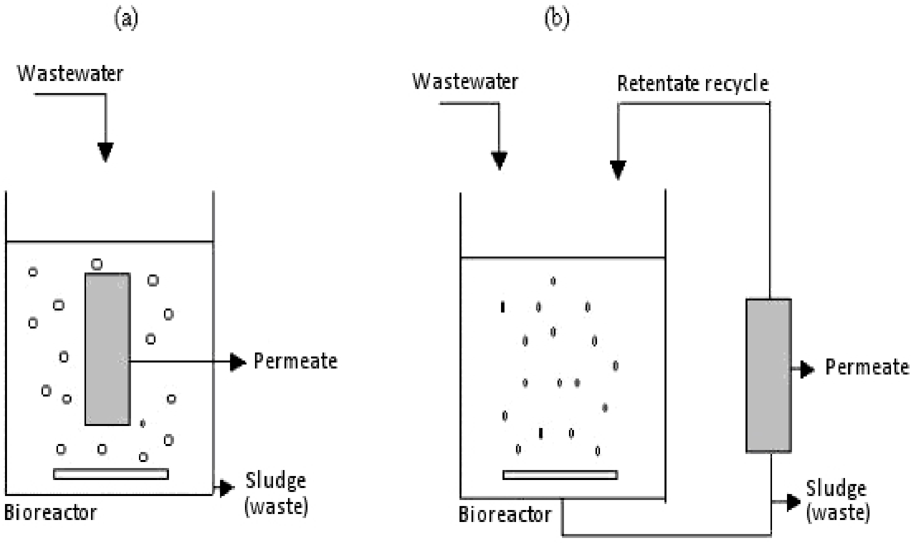


Figure 2.4 Configuration of MBR (a) Submerged MBR (b) Pressurized MBR (Melin et al., 2006)

The first option (a) is more often applied to treat municipal wastewater (Melin et al., 2006), and it can be used both hollow fiber membranes (horizontal or vertical) and flat sheet membranes (vertical). Both system are aerated at the lower part of the bioreactor, and permeate is removed by suction (Oever, 2005). In side-stream (pressurized) MBR systems (b), tubular membranes (horizontal or vertical) are placed outside the bioreactor and fed by pump.

For the submerged membrane configuration, mostly the aeration is performed with a coarse bubble diffuser. Although this system is not efficient in terms of oxygen transfer, the coarse bubble provides a cross-flow velocity approximately 1 m/s (Coppen, 2004) over the surface of the membrane. Thus, clogging that may occur on the membrane surface is prevented and of course the flux is maintained through the membrane. Consequently, requires less cleaning needs compared with side-stream (pressurized) system.

Contrary the submerged system, in the side-stream (pressurized) configuration, aeration is performed with a fine bubble diffuser. Compared to the coarse bubble, the efficient of fine-bubble is much better. The cross-flow velocity used in this system is approximately the range of 2-4 m/s (Coppen, 2004). As shown in below table, the operational flux value is higher than submerged system. One of the disadvantages of this is the clogging that frequently occurs on the membrane surface.

The energy demand of the submerged system can be lower than the pressurized (side stream) systems and submerged systems can be operated at a lower flux, demanding more membrane area (Table 2.4 and Table 2.5). In submerged configurations, aeration is considered as one of the major parameter on process performances both hydraulically and biologically. Aeration maintains solids in suspension, scours the membrane surface and provides oxygen to the biomass leading to a better biodegradability and cell synthesis.

Table 2.4 Comparison of filtration conditions for pressurized and submerged MBR System

	Side-Stream (Pressurized) MBR System	**Submerged MBR System**
Manufacturer	ZENON	ZENON
Model	Permaflow Z-8	ZeeWeed ZW-500
Surface Area (m^2)	2	46
Permeate Flux ($l/m^2.h$)	50-100	20-50
Pressure (bar)	4	0.2-0.5
Air Flow Rate (m^3/h)	-	40
Energy For Filtration (kWh/m^3)	4-12	0.3-0,6

In the side-stream (pressurized) MBR systems, the value of permeate flux is between the 50-100 $l/m^2.h$ and TMP (Trans Membrane Pressure) is about 4 bar. Whereas the submerged MBR configuration looks to be more economical depend on energy due to permeate is removed by gravity (or by suction pump) which limits TMP at about 0.5 bar.

Table 2.5 Advantages and disadvantages of MBR configurations (Till et al., 2001)

Submerged Membrane System	**Side-Stream Membrane System**
Aeration cost high (≈ 90%) Very low pumping costs (higher if suction pump is used) Lower flux (larger footprint) Less frequent cleaning required Lower operating costs Higher capital costs	Aeration cost low (≈ 20%) High pumping costs Higher flux (smaller footprint) More frequent cleaning required Higher operating costs Lower capital costs

To prevent clogging of membrane, both system need shear over the membrane surface. While submerged membrane systems use aeration in the reactor to ensure it, pressurized system provide this shear by means of pumping. Producing shear increases energy demands that is likely one of the reason for submerged configuration predominance.

2.6 Membrane Fouling

A decreased in the permeate flux or increase in TMP during a membrane operation is commonly explained as fouling and it occurs as a result of the interaction between membrane and mixed liquor. Fouling induces transmembrane flux reduction; when the flux reaches a threshold value, membrane washing becomes necessary (Gupta et. al., 2008).

As in regular membrane processes, fouling is a problem for membrane bioreactors by hindering the permeate flux during filtration. “This problem is influenced by the characteristics of the biomass, the operating conditions and characteristics of the membrane” (Chang et al., 2002). The cost of periodically replacing the membrane because of aging and fouling raises the operating costs and reduces the competitiveness of the membrane technology (Buetehorn et al., 2008). Fouling is also influenced by the hydrodynamic conditions, type of membrane and configuration of the unit, as well as by the presence of compounds with high molecular weight, which can be produced by microbial metabolism or introduced by the sludge growth process (Melin et al., 2006).

There have been a lot of studies about membrane fouling, and one of these studies carried out by Redjenovicl, Matosk, Mijatovic, Petrovicl & Barcelo, (2008) and the main causes of membrane fouling are listed as follows:

1. Adsorption of macromolecular and colloidal matter
2. Growth of biofilms on the membrane surface
3. Precipitation of inorganic matter
4. Aging of membrane

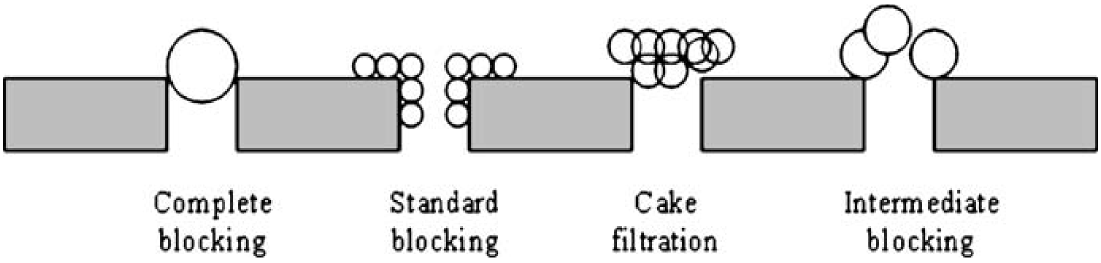


Figure 2.5 Fouling Mechanism (Redjenovicl et. al., 2008)

According to the Figure 2.5 described above, the fouling of the membrane occurs as:

1. Complete blocking caused by occlusion of pores by the particles with no particle superimposition
2. Standard blocking where particles smaller than the membrane pore size deposit onto the pore walls thus reducing the pore size
3. Cake filtration where particles larger than the membrane pore size deposit onto the membrane surface
4. Intermediate blocking caused by occlusion of pores by particles with particle superimposition

2.7 Membrane Cleaning

The frequency of cleaning which membranes need to be cleaned can be estimated by process optimization. Cleaning can be hydraulic, mechanical and chemical. Three key parameters can be adapted to control fouling that occurs in MBR operation.

1. Reversible fouling that can be removed by physical cleaning
2. Irreversible fouling that can be removed by chemical cleaning
3. Irremediable fouling that cannot be removed by any cleaning

The physical cleaning is normally accomplished either by back-flashing or stopping the permeate flow and only continuing scour air (relaxation). Physical cleaning is no chemical demand and it is a simple cleaning method. In an article published by Judd (2006), is specified that most of MBR facilities use relaxation comparatively flushing. It is not possible to remove all the material accumulated on the membrane surface using only physical cleaning method. So, chemical cleaning which is an effective method is used to remove more strongly materials accumulated on the membrane surface. Chemical cleaning is carried out mostly with sodium hypochlorite and sodium hydroxide to remove organic material or acidic solution like oxalic acid to remove inorganic material. Chemical cleaning is generally performed by adding the chemical into the back flush water. The chemical cleaning procedure last 60-180 min. and it is only occurs once or twice a year especially for municipal wastewater. Sometimes MBR systems employ chemical maintenance cleaning on a weekly basis, which lasts 30-60 min. The clogging accumulated on the membrane surface cannot be removed by usual method is named "Irremediable Fouling". This fouling determines the membrane life and generally builds up over the years of operation.

All systems also include techniques for continually cleaning the system to maintain membrane life and keep the system operational for as long as possible. Aeration intensity over the submerged membrane surface is recognized as the key operational parameter in preventing cake formation on the membrane surface in the submerged configuration (Ueda, Hata, Kikuoka & Seino, 1997). But membrane aeration is the most important item that increases operating cost because of significantly needs to the energy demand. So, recent years a lot of researches have been focused on reducing aeration without reducing the value of the permeate flux. Reducing permeate flux value reduces the fouling which is a reason of the needed more installed membrane module and hence in the increase of the capital cost of MBR installation.

In addition to the foregoing, to ensure a stable operation the intermittent operation has gained importance in recent years. Most municipal wastewater treated with submerged MBR operates at net fluxes of 20-30 L/m^2.h with the relaxation period every 9 min filtration and 1 min. relaxation as shown in Figure 2.6 (Toray Engineering Manuel, 2009).

Figure 2.6 Recommended time chart for intermittent filtration

As mentioned above to control the fouling, the most important strategies are pretreatment of feed wastewater, mixed liquor modification and optimization of physical and chemical cleaning.

2.8 Membrane Operation

Filtration performances are under the influence of different operating parameters and controls items. A well MBR operation depends on the requirements for reliability of operation. The required measurements should be checked periodically as well. All measurement should be installed and used according to the manufacturer’s instruction. The operations of the minimum measuring instruments for MBR are specified in Table 2.6.

Table 2.6 Measurements items for MBR operation (Toray Engineering Manuel, 2009).

Recommended for Measurements	**Target**
Scouring air flow rate on scouring air distribution pipe of per train	Control of scouring air flow is needed to avoid membrane element damage caused by excessive aeration.
Diffusion pressure on blower	This measurement could be used as an indicator for the blocking of the air diffuser
Permeate water flow rate on permeate collector	Control of flow and flux rate
Return sludge flow rate on return sludge pipe	Control of return sludge flow rate and MLSS in MBR tank
Excess sludge on excess sludge outlet pipe	Control of excess sludge discharge
Trans Membrane Pressure between the membrane tank and in the permeate collector	Control of membrane permeability
Water level of biological tank and MBR tank	Control of level tank (Stop filtration if level is too low or stop MBR inlet if level is too high) and control of production capacity in case of gravity filtration
Mixed liquor temperature of MBR tank	Viscosity of sludge and flux may vary with the liquid temperature. So liquid temperature is an important parameter for the operation of the membranes
DO value of the biological tank	DO should be measured in the biological tank to check if the biological treatment under the good condition. DO concentrations should be above 1 mg/L at the biological tank and will go up in the MBR tank because of aeration. High oxygen concentration may limit the denitrification capacity. If the oxygen concentration is too high, a part of the sludge recirculation should go directly to nitrification
pH value of the biological tank	It should be measured at the inlet of the biological tank to avoid limiting biological treatment
MLSS value of the biological tank	To control amount of biomass and viscosity, MLSS measurement is needed
Raw water and permeate water quality	Monitoring of raw water and treated water

2.9 Operating Parameters

2.9.1 Permeability

Permeability is defined as a condition of membrane which is relative with flux for 1 m^2 membrane area at 1 bar TMP and fixed temperature. Permeability is the key parameter used to monitor membrane performance like flux and Trans Membrane Pressure (TMP) are typically monitored online and can be calculated from the following formula:

$$\text{Permeability}\ (T) = (\text{Flow} \times 1000) / (\text{Membrane Area} \times \text{TMP})$$

Where;

Permeability	: $L/m^2.bar$
Flow	: m^3/h
Membrane area	: m^2
TMP	: bar

The permeability depends on the temperature because the viscosity and the membrane conditions are different at different temperatures. To calculate a permeability value at different temperature the following formula can be used;

$$\text{Permeability}\ (20^oC) = \text{Permeability}\ (T) \times 1.022^{\Delta t}$$

Where;

Permeability (T) : permeability at given temperature ($L/m^2.bar$)

Permeability (20 °C): normalized permeability at 20 °C ($L/m^2.bar$)

Δt : always a positive number if $T > 20$ °C, $\Delta t = T-20$
if $T < 20$ °C, $\Delta t = 20-T$

Permeability calculation example is given below:

Production flow (m^3/h) : 50
Installed membrane area (m^2) : 2.015
TMP (bar) : 0.01
Temperature (°C) : 15
MLSS (g/L) : 15

Calculation;

Permeability (15 °C) = 50 x 1000 / (2.015 x 0.01) = 2.481 m^2/h.bar
Permeability (18 °C) = Permeability (15 °C) x $1.022^{(18 - 15°C)}$ = 2.648 m^2/h.bar

As a result, some practical information about permeability is:

- Permeability is different at different flux rates and highest permeabilities can be achieved only with maximum flux rate
- Permeability should calculated periodically at the same flux and MLSS concentration

As seen in the above formulas and explanations, permeability is different at the different flux rates and it is only possible with the maximum value of flux can be achieved to the highest permeability value. Eventually, it must be taken into account the permeability value should measured or calculated every time at the same flux and MLSS concentration (e.g. max. day or daily average flow/flux at design MLSS)

2.9.2 Flux

It can be described as the amounts of flow passing through a unit of the membrane area and generally called permeate flux and it is affected by a number of factors. On the permeate flux, the following parameters are decisive (Stephenson, Judd, Jefferson & Brinde, 2000).

- The membrane resistance
- The operational driving force per unit membrane area
- The hydrodynamic conditions at the membrane liquid: liquid surface
- The fouling and subsequent cleaning of the membrane surface

Permeate flux decrease means that decline in the flux and this decline rate depend on the fouling mechanism like standard pore blocking model, pore blocking model, cake build model (Gupta et al., 2008).

The increasing of the fouling on the membrane surface is directly proportional to permeate flux and it can be described by the following formula;

$$J = \Delta P/\mu R$$

Where,

J : permeate flux (m^3/m^2s)

ΔP : pressure drop across the membrane (N/m^2)

μ : absolute viscosity of the water (Ns/m^2)

R : total resistance of the membrane against the flux (L/m) and described by the following formula;

$$R = R_m + R_i + R_c$$

Where,

R_m : hydraulic resistance of the membrane (m^{-1}) in pure water

R_i : irreversible fouling resistance of the membrane (m^{-1})

R_c : resistance due to particle deposit at the membrane surface and it increases with roughness of membrane (m^{-1})

2.9.3 Critical Flux

The critical flux terming was firstly referred at a study carried out by Field et al. in 1995 and specified that the fouling occurred on the membrane surface can be ignored under the critical flux. Below this threshold value the flux is directly proportional to Trans Membrane Pressure. This manner, the cleaning operation is not performed frequently and at a low Trans Membrane Pressure prevents membrane from an irreversible fouling. Fouling can be occurred reversible or irreversible. Irreversible fouling, which is not removed by simple cleaning techniques, takes place a result of the decreasing flux for a long time.

2.9.4 TMP (Trans Membrane Pressure)

Trans Membrane Pressure (Driving Force) can be defined as the difference between the average static on the suspension side and the dynamic pressure on the permeate side (Sarioglu, 2007) and described as the following formula:

$$\Delta P_{TM} = \textit{Static Pressure} - \textit{Dynamic Pressure}$$

Where;

ΔP_{TM} : Transmembrane pressure (bar, kPa)

The TMP or in other word driving force and flux value are involved and any of them can be stable for design purposes and described below.

2.9.5 The Relations Between TMP and Flux at MBR Operation

There are two distinct modes of operation available in the submerged membrane bioreactor system:

- Constant TMP operation
- Constant Flux operation

For the constant TMP operation, flux decreases with increasing fouling which is initially rapid, but then becomes more gradual. In a constant flux operation, fouling cause increase in TMP that is initially gradual, accelerated after cleaning and more preferable operational mode for MBR owing to effectiveness (Gupta et al., 2008).

As a result of the low pressure difference and low flux, the thickness of sludge accumulated on the membrane surface will be small and both operational parameters will be associated only with each other and with membrane resistance. Depending on these operating conditions, the basic logic of the filtration process is controlling the membrane and the physical characteristic of membrane will be help to define the flux. During the operation, more solids and materials are accumulated on the membrane surface and related to the increasing of TMP the fouling increases.

2.10 Process and System Design of MBR

The purpose of this study is to investigate the optimum design parameters of the Membrane Bioreactor Systems because of has a wide range of design and as a whole to determine the ideal conditions of wastewater treatment plant with MBR systems.

The design of the MBR system is evaluated in three distinct categories during the process design:

a. The selection and operation of pre-treatment process
b. The sizing of the MBR tank
c. The mechanical design of the membrane system

The design of the pre-treatment system is essential for MBR operation since membran modules are susceptible to stilting of fibrous materials derived from wastewater. The selected pre-treatment should assure the removal of FOG, grit & sand as well as other material which may clog or damage the membrane. It is an important factor for improving membrane life and minimizing future membrane replacement cost. Regarding primary sedimentation, it is not economically viable for small-medium sized MBR plants (< 50.000 m^3/d), except for cases of retrofitting or upgrading of an existing CAS. However for larger plants, given its advantages (smaller bioreactor volumes, reduced inert solids in the bioreactor, increased energy recovery, etc.), primary clarification can be considered. It is selection should be a compromise between energy and land cost (Delgado, Villarroel, Gonzales &

Morales, 2011). Since a pre-treatment optimization could induce a better bioavailability of the substrate, it would also enhance the biological treatment.

2.10.1 Process Configuration

For optimum design and of course for optimum operational result, the complete process design (pre-treatment, biological process, membrane filtration and sludge treatment) should be made fully. Membrane system design for a MBR process, of course, is only a part of the overall system.

MBR represents the most widely used configuration in applications. This section gives some design and operation considerations. According to the needs, the following points should be taken into account respectively when designing the MBR system:

a) Storm water flows
b) Physical/chemical pre-treatment (coarse bar screen, aerated grit and sand removal, fine screen, FOG removal, coagulation, pH adjustment, etc.)
c) Flow equalization (optional)
d) Biological treatment (carbon, nitrogen and phosphorous removal)
e) Membrane filtration
f) If required, treated water disinfection
g) Sludge treatment

Designers of MBR systems require only basic information about the wastewater characteristics, (e.g., influent characteristics, effluent requirements, flow data) to design an MBR system. Depending on effluent requirements, certain supplementary options can be included with the MBR system. For example, chemical addition (at various places in the treatment chain, including: before the primary settling tank; before the secondary settling tank; and before the MBR or final filters) for phosphorus removal can be included in an MBR system if needed to achieve low phosphorus concentrations in the effluent (EPA, 2007).

The membrane bioreactor system compared to conventional system is an activated sludge process which solid-liquid separation is carried out by membrane filtration instead of secondary clarifier as shown Figure 2.7. As noted, all treatment steps must be designed to ensure optimum operation of the MBR system.

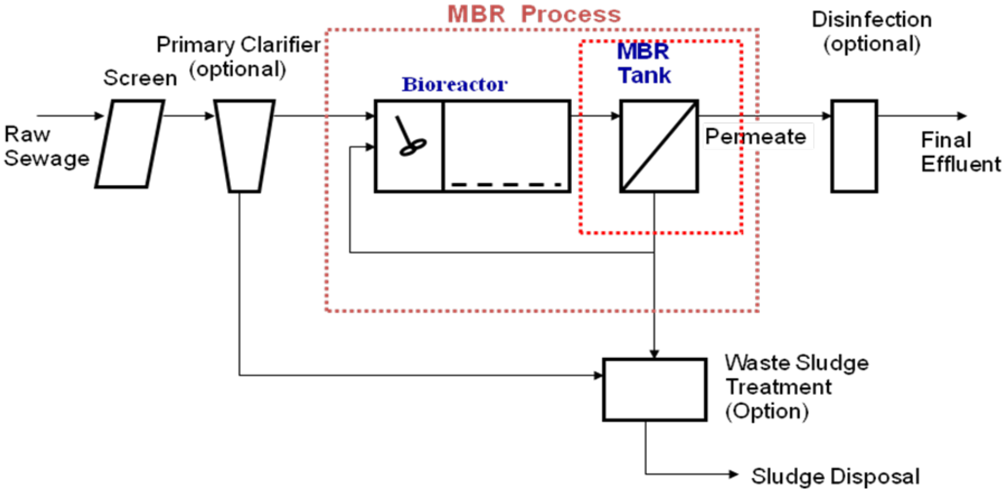


Figure 2.7 Treatment steps of MBR process

As stated previous sections, MBR systems offer an uncomplicated plant structure and compact footprint, as well as the additional advantage in the quality of effluent water. The configuration of membrane filtration has an essential importance to the design of MBR plants. It is determined by specific plant preconditions and the process technology requirements relating to the membranes.

For a membrane bioreactor process with submerged configuration two approaches are possible. One of these configurations is named as integrated system which membrane module takes places directly into the aeration tank. The other one is the separated system which membrane module is in a separated tank excluding aeration tank.

1. **Integrated System:** The biological treatment and membrane module in a single tank, especially this mechanism is primarily preferred for small plants or containerized system.

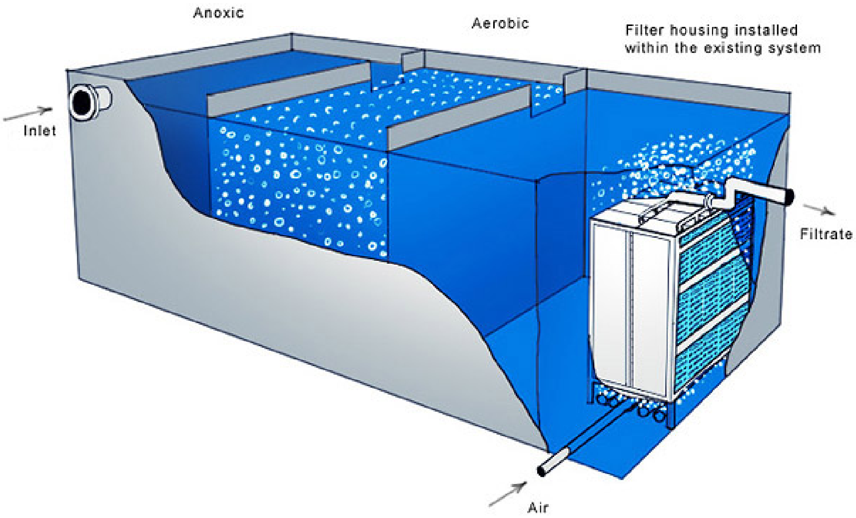


Figure 2.8 Integrated concept of MBR system (Image from http://www.atacsolution.com)

2. **Separated System:** The submerged membrane module in a separated filtration tank, preferable for larger process with good maintenance.

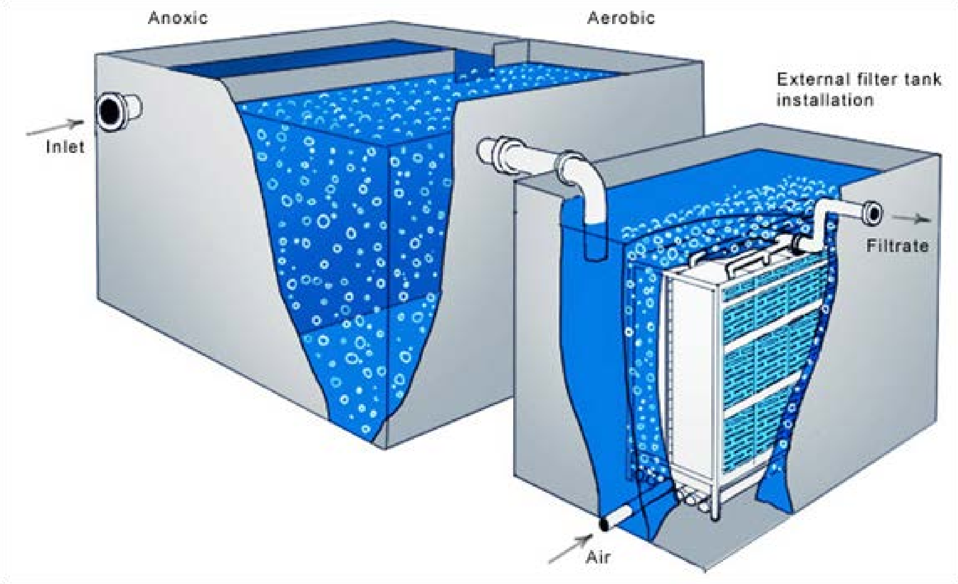


Figure 2.9 Separated concept of MBR system (Image from http://www.atacsolution.com)

2.10.2 Mechanical Pre-Treatment of Feed Water

A lot of studies in these subjects are intended to minimize operating cost and one of the basic ways to accomplish this is definitely a well-designed pre-treatment system. It shows that this issue is an essential pre-requisite for MBR systems.

Cote et al. are specified that "The first generation of membrane bioreactors (MBR) in the 1970s and 80s were built with large diameter tubular membranes and were primarily used for small-scale industrials effluents containing little trash. Pre-treatment to MBR first became an issue when hollow fibers and plate immersed membranes were introduced in the 90s for application to municipal wastewater. Today, municipal MBRs with capacities up to 50,000 m^3/d are in operation and much larger systems are in the construction, design or planning stages. Current research efforts aimed at reducing the cost of the technology will result in increasing membrane packing density and reducing membrane scouring aeration. This evolution makes it increasingly important to install adequate pre-treatment to protect membranes at the core of a MBR" (Cote et al., 2006).

The wastewater contains large floating objects, fibrous material or other foreign objects, which will cause problems for treatment and pumping equipment. These non-degradable objects have to be removed or they may lead to blockages. These objects are called screenings. Manuel bar screens may be adequate for smaller plants; however, mechanical screens are normally used to remove the screenings from the water.

Santos and Judd are specified that "Membranes are very sensitive to damage with coarse solids such as plastics, leaves, rags and fine particles like hair from wastewater. In fact, a lack of good pre-treatment/screening has been recognized as a key technical problem of MBR operation" (Santos & Judd, 2010).

Cote et al. are specified that "The potential negative impacts of poor pre-treatment on the membranes themselves may include 1) build-up of trash, hair, lint and other fibrous materials, 2) increased risk of sludge accumulation and 3) damage to the membrane. Eventually, these impacts could result in a reduction of the hydraulic capacity of the plant and degradation of the effluent quality. In addition, trash in the mixed liquor can plug the coarse bubble aerators used to scour the membranes. These aerators are typically pipes with holes ranging in size between 5–10 mm. A plugged aerator can deprive the membranes above it from scouring air and significantly decrease their efficiency" (Cote et al., 2006).

In order to ensure a stable and reliable operational of municipal MBR plants, an enhanced mechanical pre-treatment of the raw wastewater is essential. Removal of hair, fibrous material and other contraries which can lead to operational problems at the membrane modules is of particular importance (Schier, Frechen & Fischer, 2009).

There is still discussion ongoing how to design the optimal pre-treatment system. This is mainly due to the fact that still today there is relatively poor knowledge about the ability of different pre-treatment units. In order to obtain the best operational efficiency, many membrane manufacturers requires an effective grit/grease removal system and a 3 mm fine screening system as minimum requirements for the mechanical treatment prior to the MBR. "Screening requirements for hollow fiber and flat sheet configurations are differ: hollow fiber membranes typically require 1-2 mm screening, while flat sheet membranes require 2-3 mm screenings" (Wallis-Lage & Hemken, 2006).

2.10.2.1 Recommendation of Fine Screen

Coppen is specified that "Mechanical screens come with different apertures and types. Generally, all screens with an aperture less than 10 mm diameter or gap for slot opening are called fine screens. The choice of aperture will affect the quantity and quality of screening captured. If using fine screening in conjunction with a gravity flow system, faucal matter will be captured together with screenings. This has to be borne in mind when designing the screening handling system. Various types of screening equipment are used to suit different applications” (Coppen, 2004).

Adequate pre-treatment including fine screening is essential to the stable, long-term operation of membrane bioreactors (MBR) used to treat municipal wastewater. "The amount of screenings generated by a screen with 1-2 mm size openings ranges between 10-25 dry mg/L. The cost of fine screening represents less than 3 % of the total investment cost for a MBR-based wastewater treatment facility” (Cote et al,. 2006).

Many different types of fine screens are available on the market. The main difference between them is the effectiveness of particle removal. "Screens with mesh or punched hole perforations are more effective than bar or wedge-wire screens, and the latter types should be avoided in all situations" (Toray Engineering Manuel, 2009).

The best data available in the literature on MBR pre-treatment are contained in an IWA published report of the pilot studies in Beverwijk, The Netherlands (van der Roest, 2002). The removal efficiency of different screens over several months is listed in Table 2.7. It is interesting to note that the 7.2 mm bar screen removes very little solids, while the 0.5 mm screens remove a large amount of paper fibers, in addition to hair and trash. Primary clarification ahead of fine screening actually removes the bulk of the screenings and would significantly reduce the solids loading to the fine screens. The authors concluded that 1.0 mm-hole (not slots) screening is required to protect plate or hollow fiber immersed membranes.

Table 2.7 Screenings contents of typical sewage with different screen configurations

Feed	Screen	Screenings Dry (mg/L)	Comment
Raw WW	Bar screen (7.2 mm slots)	< 1.0	Very little removal
Raw WW	Vibrating screen (0.75 mm holes)	14	Removal of essential all trash (hair, seeds, etc)
Raw WW	Brush screen (0.75 mm holes)	23	Removal of essential all trash (hair, seeds, etc)
Raw WW	Rotary drum screen (0.5 mm holes)	94	Significant removal of paper fibers that could be degraded in the MBR
Settled WW	Rotary drum screen (0.5 mm holes)	2.8	Primary clarification remove most trash; the screen protects the membranes

TORAY also recommends the following features of the screening system:

- The opening size of the screen must be 3 mm or less.
- Preferred screens are mesh or punched-hole perforations, traveling band or rotating drum, operated with a mat and complete with a screenings washer/compactor
- Any by-pass or carryover must not be allowed. The screen system should be designed for the maximum flow with 1 stand-by screen to allow maintenance work without treatment interruption.
- The screen should have a low head loss. In-channel screens without any additional pumping to the screen are preferable.
- The debris removal system should have optimum efficiency and should handle all anticipated particle loading and remove them safely from the raw water.
- A coarse bar screen should be installed at the inlet of the plant to protect the following treatment steps from mechanical damage by stones and other large debris.

ZENON’s recommendation for MBR pretreatment is a multi-step approach involving either 1) coarse screening (≤ 6 mm), grit/grease removal and ≤ 2 mm fine screening, or 2) coarse screening (≤ 25 mm), primary clarification and ≤ 2 mm fine screening.

Protecting the membrane bioreactor investment, fine screen for membrane bioreactor system is an essential pretreatment step to prevent unwanted solids in the waste stream from entering the membrane tank This prudent design measure minimizes solids accumulation and protects the membranes from damaging debris and particles, resulting in extended membrane life, reduced operating costs, higher quality sludge and trouble-free operation.

2.10.2.2 Recommendation of Grit/Grease Removal

There is no special grit/grease removing requirements for MBR systems. Only well-designed systems that are used for conventional activated sludge process is sufficient for MBR systems. But, membran manufacturers recommend locating the grit/grease removal systems after the coarse screen and another point to be considered that maximum acceptable amount of the fat, oil and grease (FOG) is < 50 mg/L at the inlet of the biological treatment step. Typical grease level found in domestic wastewater is not affect the membrane performance (Toray Engineering Manuel, 2009).

Some of the proposed systems are as follows:

- Conventional aerated grit and sand removal processes separate fine sand particles, grit and fat from the inlet of the plant and reduce the normal component of grease at municipal sewage treatment plants.
- Flotation units are often applied at industrial waste water treatment plants. For sewage treatment plants it can be used effectively to separate the grease if no sand particles are expected.
- Fine screens, operated with a mat can reduce FOG loading significantly.

CHAPTER THREE
MODELING & SIMULATION PROGRAMS USED IN ACTIVATED SLUDGE PROCESSES

3.1 Introduction

It is in human nature to want to understand dynamic systems, control them, and above all predict their future behavior. "During the last century, this desire has led to inter-disciplinary research into modeling and simulation, bringing together results from mathematics, computer science, cognitive sciences, and a variety of application-domain-specific research. Modeling covers the understanding and representation of structure and behavior at an abstract level, whereas simulation produces behavior as a function of time based on an abstract model and initial conditions" (Vangheluwe, 2001).

Starting at the beginning of the 1950s and showing great improvements in recent years, modeling has gained a separate inter-disciplinary research area different from the computer science, mathematics, etc. Modeling and simulation is getting information about how something will behave without actually testing it in real life. For instance, if we wanted to design an activated sludge process, but we were not sure how to be the behavior of the wastewater after each treatment unit (like after screening or primary sedimentation tank, etc.), then we would be able to use a computer simulation program. Hereby, we are getting useful insights about different decisions and we could have more prediction before building the process.

The basic principle of the modeling and simulation used in the activated sludge process, constitute knowledge about behavior systems and to create a better operational conditions. Especially, in the recent years depending on the development of the MBR systems, most of the modeling and simulation program have been optimized. Some of these programs are briefly summarized below.

3.2 BioWin

BioWin is widely recognized as a powerful, accurate and easy to use dynamic wastewater treatment process modeling and simulation package. It was developed by EnviroSim Inc which is located in Canada and provides simulation software solution and consulting services to both municipal and industrial wastewater process engineers around the world. Process modeling, simulation technology, last innovations in graphic and performance tools helps to simulate and evaluate of results.

BioWin is a Microsoft Windows-based simulator used world-wide in the analysis and design of wastewater treatment plants. An example of configuration set up in BioWin including nutrient removal and an example for process units are given in Figure 3.1 and 3.2, respectively.

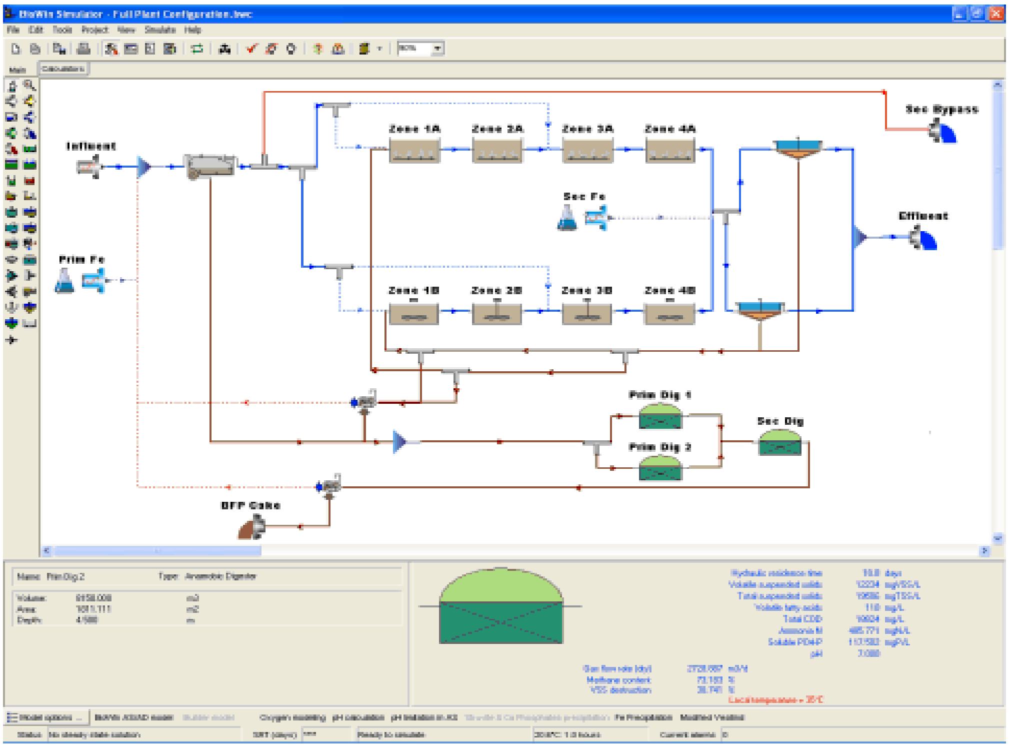
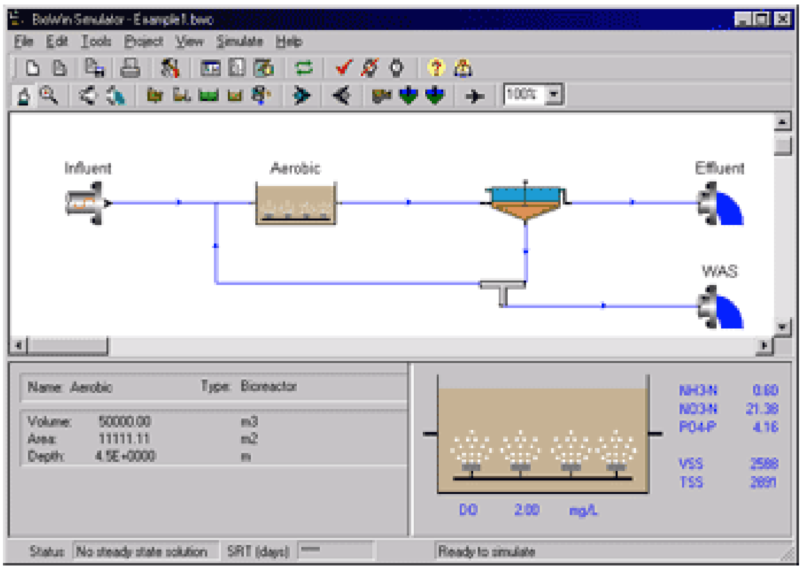


Figure 3.1 Example of a process configuration set up in BioWin (Image from http://www.envirosim.com/products/bw32/bw32intro.php)



Name: Aerobic
Type: Bioreactor
Volume: 50000.00 m3
Area: 11111.11 m2
Depth: 4.5E+0000 m

NH3-N 0.80
NO3-N 21.38
PO4-P 4.16
VSS 2588
TSS 2891
DO 2.00 mg/L

Status: No steady state solution
SRT (days) —
Ready to simulate

Figure 3.2 Example of a process unit (Image from http://www.envirosim.com/products/biowinpopup.html)

Many different process units can be included to build a specific treatment plant configuration:

- Various influent elements for setting up wastewater inputs, storm flow inputs, or methanol addition streams, influent elements may be COD or BOD based
- Continuous flow bioreactors incorporating sophisticated means for simulating the performance of diffused aeration systems
- Model builder element – specify rate and stoichiometry equation for your custom process
- Various sequencing batch reactor (SBR) modules: single tank units, or SBRs with one or two hydraulically-linked prezones that are either continuously mixed or that allow settling of solids when the decant zone is in a settling phase
- Aerobic digesters
- Anaerobic digesters
- Grit removal tanks
- Equalization tanks
- Variable volume/batch reactors
- Primary settling tanks
- Activated primary settling tanks

- Secondary settling tanks, where solid removal performance is either specified by the user, or where sludge settling behavior is based on flux theory using a one-dimensional model. Biological reaction in secondary settling tanks may be modeled
- A generic dewatering unit where the user specifies both solids capture and flow split between the thickened and un-thickened streams. This unit can be applied to simulating a range of dewatering process such as centrifuges, belt presses, dissolved air flotation units, etc.
- Mixing and splitters for directing flow between units in the configuration. The users have full flexibility for specifying details of splits in streams (by actual rate, fraction, ratio, flow pacing, according to a time schedule, etc.)

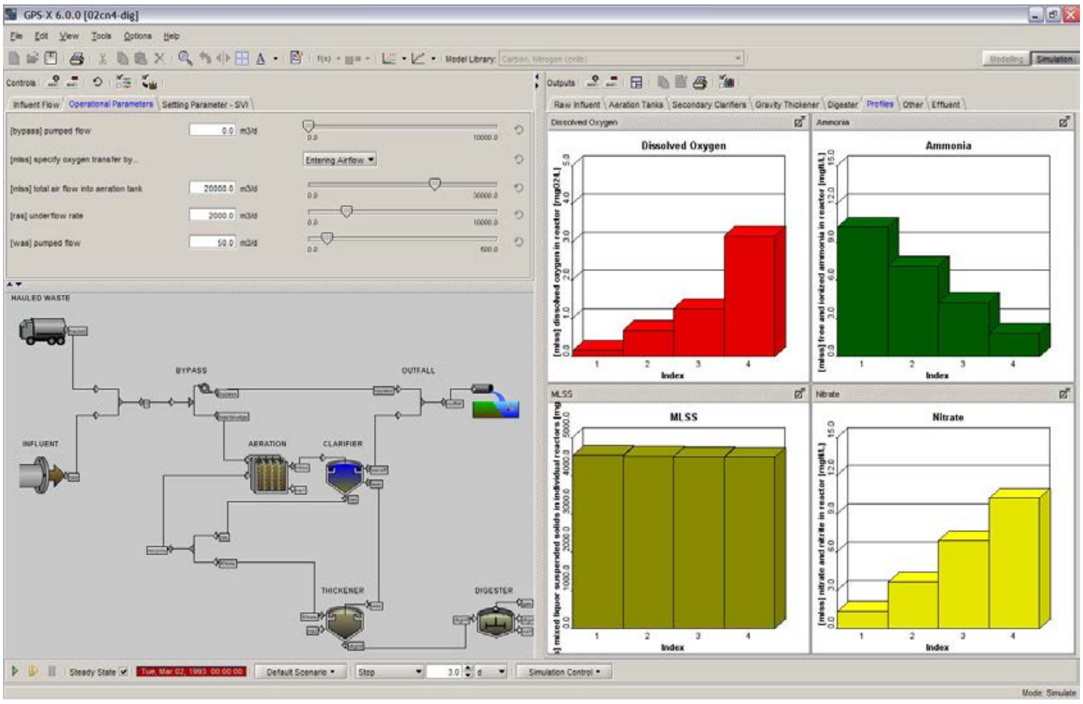
“The facility to view simulation results rapidly, and in details of paramount importance in the design and analysis of systems. BioWin incorporates an album for this purpose. The Album consists of a series of tabbed pages (somewhat like recent spreadsheet programs) showing simulation results in tubular and/or graphical format. BioWin offers a number of features to aid in creating attractive, Professional reports, and includes its own internal. Notes editor help keep track of Project details. It is very easy to get results from BioWin into a word processor or spreadsheet. Charts, tables, system configuration layouts, etc. can be copied and pasted from BioWin to reports. Tables can be exported as tabbed text and then quickly converted to tables” (Retrieved from http://www.envirosim.com/products/bw32/bw32intro.php).

3.3 GPS-X

GPS-X is a modular, multi-purpose computer program for the modeling and simulation of municipal and industrial wastewater treatment plants and developed by Hydromantis Environment Software Solution Inc. which gets busy in Canadian in the field of environmental engineering and software development.

It is specified that “Whether users are designing a new facility, or simulating an existing plant, GPS-X will help user improve their own design and operating efficiency. Improve performance of treatment plant does not depend on increase in its size and complexity. User can improve capacity, operating efficiency and effluent quality by properly optimizing existing facilities. Then the result in dramatic capital savings and lower operating costs" (Retrieved from http://www.technotrade.com.pk/20/GPSX_Waste_Water_Treatment_Simulation_Software/).

It is specified that "GPS-X is the state-of-the-art in wastewater process simulation. Featuring the industry's easiest to use interface (Figure 3.3) and most comprehensive suite of wastewater models, GPS-X provides engineers with a proven tool for process analysis" (Retrieved from http://www.hydromantis.com/GPS-X.html).



[bypass] pumped flow 0.0 m3/d
[mlss] specify oxygen transfer by... Entering Airflow
[mlss] total air flow into aeration tank 20000.0 m3/d
[ras] underflow rate 2000.0 m3/d
[was] pumped flow 50.0 m3/d

Figure 3.3 The interface of GPS-X (Image from http://www.hydromantis.com)

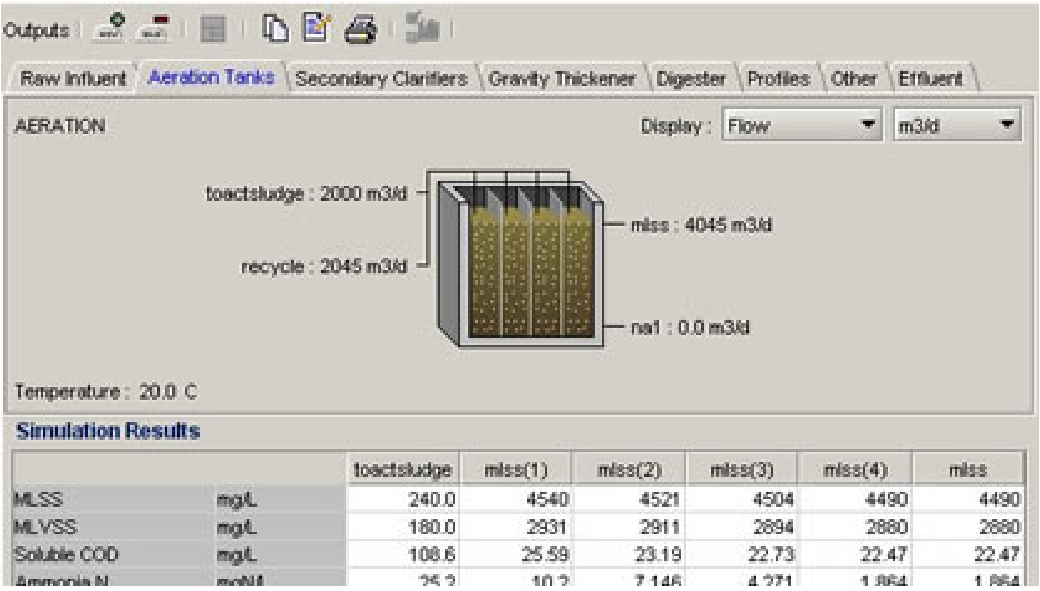
Advanced tools such as Model Developer allow for easy biological model manipulation in matrix format. All GPS-X input and output menus, as well as the new simulation results summaries, can be edited and customized by the user. "The features of the GPS-X are briefly summarized with the following:

- Accurately size unit process
- Save process design time
- Minimize operational costs while meeting effluent quality requirements
- Select the best design alternatives
- Investigate process changes that are require to achieve nutrient removal in plant
- Evaluate multiple scenarios efficiently
- Predict the effect of taking one of unit processes off-line for maintenance
- Recover in the shortest possible time from plant upsets
- Accurately evaluate process control improvements
- Train operators by illustrating the effect of operating decision on plant performance
- Evaluate the economic impact of water conservation
- Control mass balances through plant
- Achieve confidence in design"

The program has an extensive library of numerical methods and process models to reduce program development time for practicing engineers and features including interactive controllers and graphics, built in analysis and optimization tools. GPS-X contains the industry's largest library of process models (Figure 3.4), covering a wide range of liquid and solids treatment. A full suite of biological models cover all common treatment processes for carbon, nitrogen, phosphorus and pH control.

A new simulation environment allows modelers quick and easy access to simulation results. Summarized output data is available to be viewed (Figure 3.5), copied and/or printed with a single mouse click.

Figure 3.4 Comprehensive library of unit process models (Image from http://www.hydromantis.com)



Display : Flow m3/d

Temperature : 20.0 C

Simulation Results

		toactsludge	mlss(1)	mlss(2)	mlss(3)	mlss(4)	mlss
MLSS	mg/L	240.0	4540	4521	4504	4490	4490
MLVSS	mg/L	180.0	2931	2911	2894	2880	2880
Soluble COD	mg/L	108.6	25.59	23.19	22.73	22.47	22.47

Figure 3.5 Streamlined simulation interface (Image from http://www.hydromantis.com)

3.4 STOAT

It is specified that “The STOAT package (STOAT = Sewage Treatment Operation and Analysis over Time) was developed by WRc (Water Research Centre registered in England) who is an independent and employee-controlled organization with an expertise built from over 80 years of national and international work. WRc has over thirty years experience of development and application of models for wastewater treatment processes and is recognized internationally for its software development” (Retrieved from http://www.wrcplc.co.uk/software.aspx).

Schütze et al. are specified that “For simulation of the activated sludge process, either the activated sludge models or BOD-based model can be chosen within STOAT or the model component included is for secondary clarifier, trickling filters, disinfection, phosphorus removal, sludge digestion, and dewatering. STOAT has been applied to many treatment plants, particularly in the UK” (Schütze, Manfred & Beck, 2002).

"STOAT is a PC based computer modeling tool designed to dynamically simulate the performance of a wastewater treatment works. The software can be used to simulate individual treatment processes or the whole treatment works, including sludge treatment processes, septic tank imports and recycles. The model enables the users to optimize the response of the works to change in the influent loads, work capacity or process operating conditions” (Retrieved from http://www.wrcplc.co.uk/software.aspx). Using STOAT can help the users:

- Improve effluent quality, reducing risk of the consent failures
- Reduce capital and operational costs
- Design treatment plants more efficiently
- Optimize treatment plant operation
- Troubleshoot operational problems
- Carry out integrated catchment simulation
- Train staff in best practices

STOAT contains a range of features which makes it the most comprehensive modeling package available, including:

- Models all common treatment process
- Offers both BOD and COD models
- New models continually being added
- Integrates with leading sewerage and river quality models
- Easy to use, with user friendly interface (Figure 3.6 and Figure 3.7)
- Includes quick build wizard
- Support for batch simulations
- Allows simplified sewer modeling
- Easy data transfer to other packages

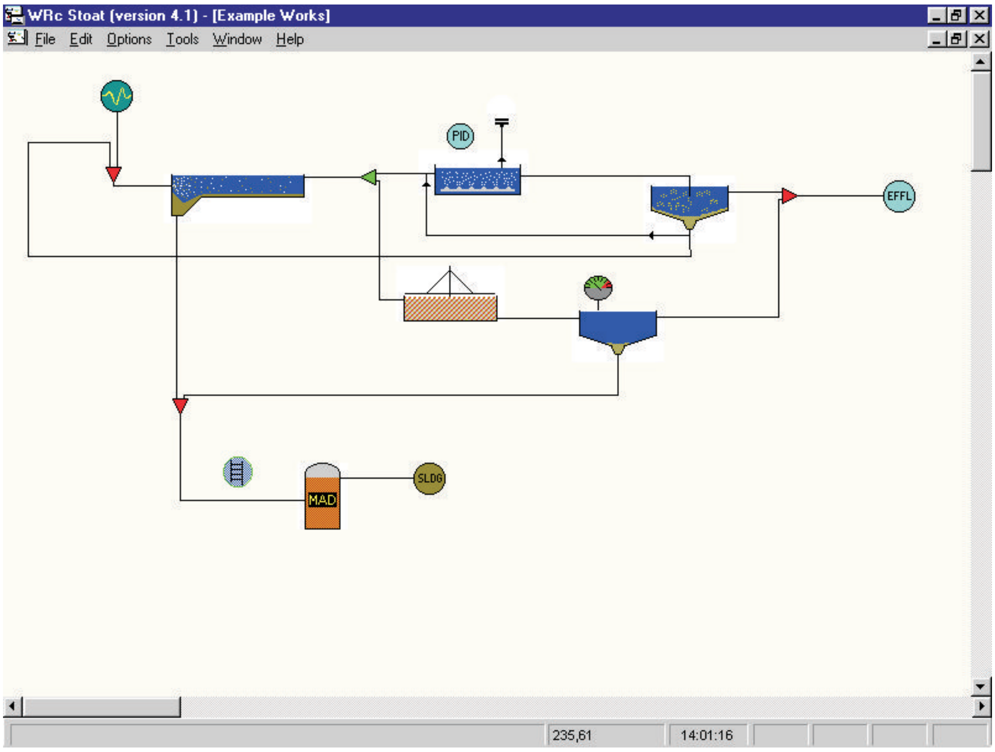
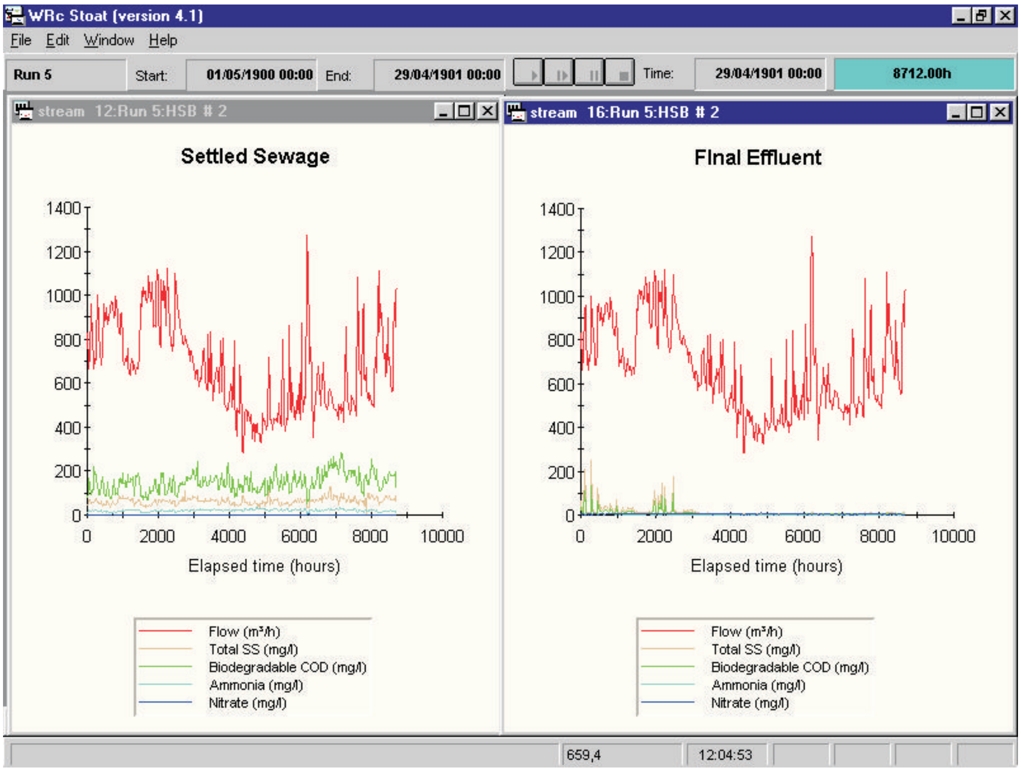


Figure 3.6 An example of the interface of STOAT (Image from http://www.wrcplc.co.uk)



Run 5 Start: 01/05/1900 00:00 End: 29/04/1901 00:00 Time: 29/04/1901 00:00 8712.00h

659,4 12:04:53

Figure 3.7 An example of the interface of STOAT (Image from http://www.wrcplc.co.uk)

3.5 WEST++

The simulation package was developed by University of Gent in Belgium. "WEST++ contains a variety of module libraries for the individual parts of the treatment plants like preliminary treatment models, the activated sludge models, the secondary clarifier models. Program developed in recent years and additional modules include modules for parameter estimation and sensitivity analysis. Particular emphasis was given to the performance of the simulations. Furthermore, the platform allows the users to specify his models, using a model specification language. WEST++ is being used in many installations, inside and outside Belgium" (Schütze et al., 2002).

As shown in Figure 3.8 and in Figure 3.9, the WEST++ modeling environment allows for component based modeling. The users connect model icons in a hierarchical fashion. From this abstract specification, together with a library of dynamics models, one single model is produced.

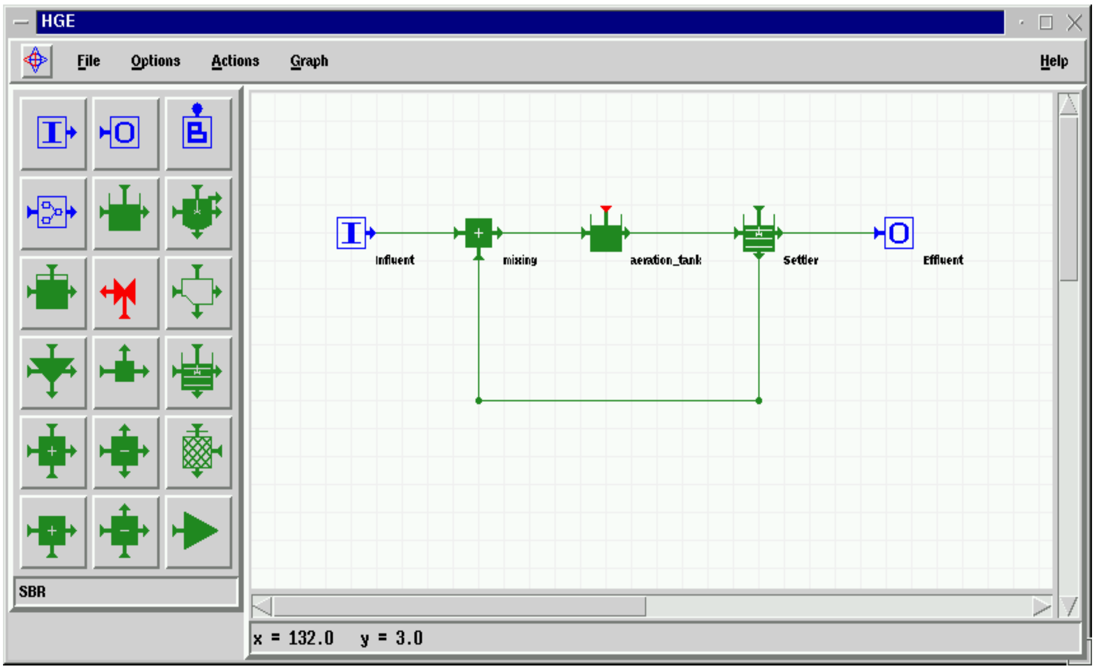
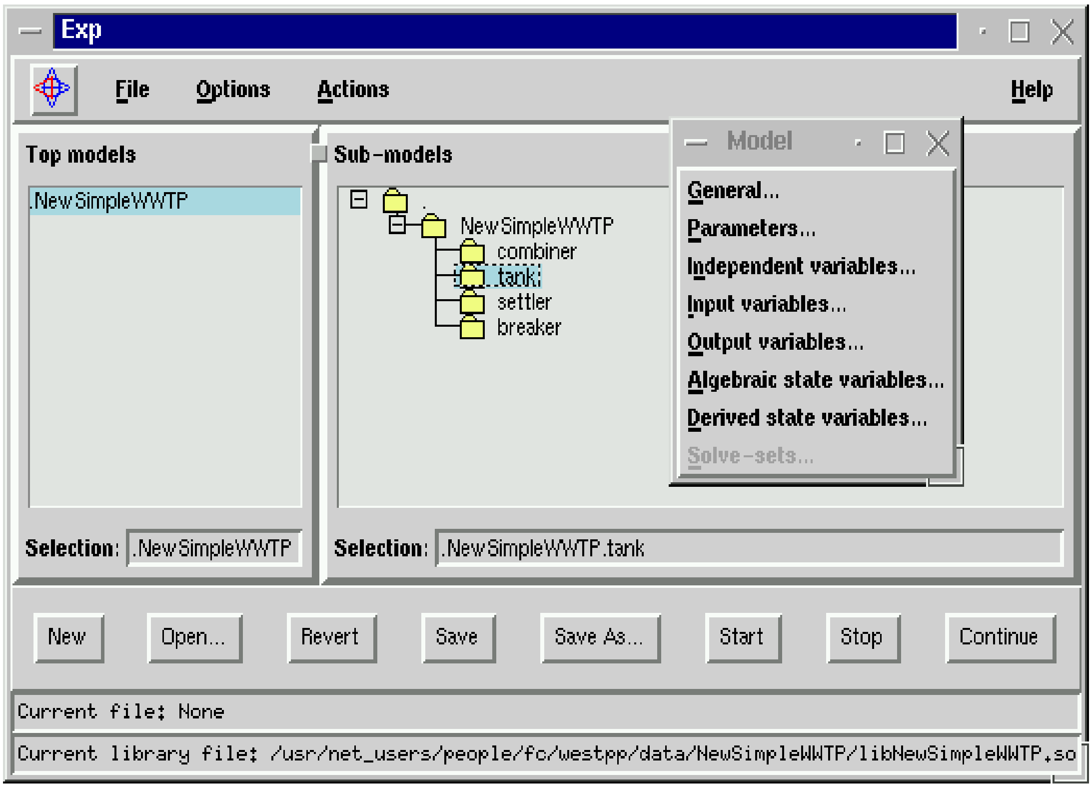


Figure 3.8 Simple WWTP model



Selection: .NewSimpleWWTP

Selection: .NewSimpleWWTP.tank

```
Current file: None
Current library file: /usr/net_users/people/fc/westpp/data/NewSimpleWWTP/libNewSimpleWWTP.so
```

Figure 3.9 An example of the interface of WEST ++

3.6 SIMBA

"The modeling and simulation package program SIMBA was developed by IFAK which is an independent research institute in Germany and gets busy in the field of process control and automation technologies and information management for automation and environmental systems" (Retrieved from http://www.ifak.eu).

It is specified that “The program based on the MATLAB/SIMULINK simulation system. SIMBA allows the users to define his treatment plant from building blocks and to freely modify and extend the building blocks of the model” (Schütze et al., 2002).

It is specified that “SIMBA has been developed simulation of the biological wastewater treatment. The program allows the modeling of wastewater systems on computers by considering the components sewer, wastewater treatment and receiving water. Simulation models can consist of single components or any combination of all combination. As shown in Figure 3.10, a plant model, consisting of primary clarifier, wastewater treatment tanks, and secondary clarifier will be graphically built up. The inflow will be defined as signal vector of volumetric flow and concentrations” (Retrieved from http://www.ifak.eu).

During the simulation, the effluent concentrations and the states of all process units of the plant will be calculated. A recent version allows parameter estimation, sensitively analysis, and controller design to be carried out in a convenient way (Schütze et al., 2002). With the current SIMBA version, the work with the models is distinctly easier. A uniform description of biological, chemical and physical processes by using an editor with built-in ASM matrix represents the core. The Figure 3.11 shows this compact presentation of complex process models.

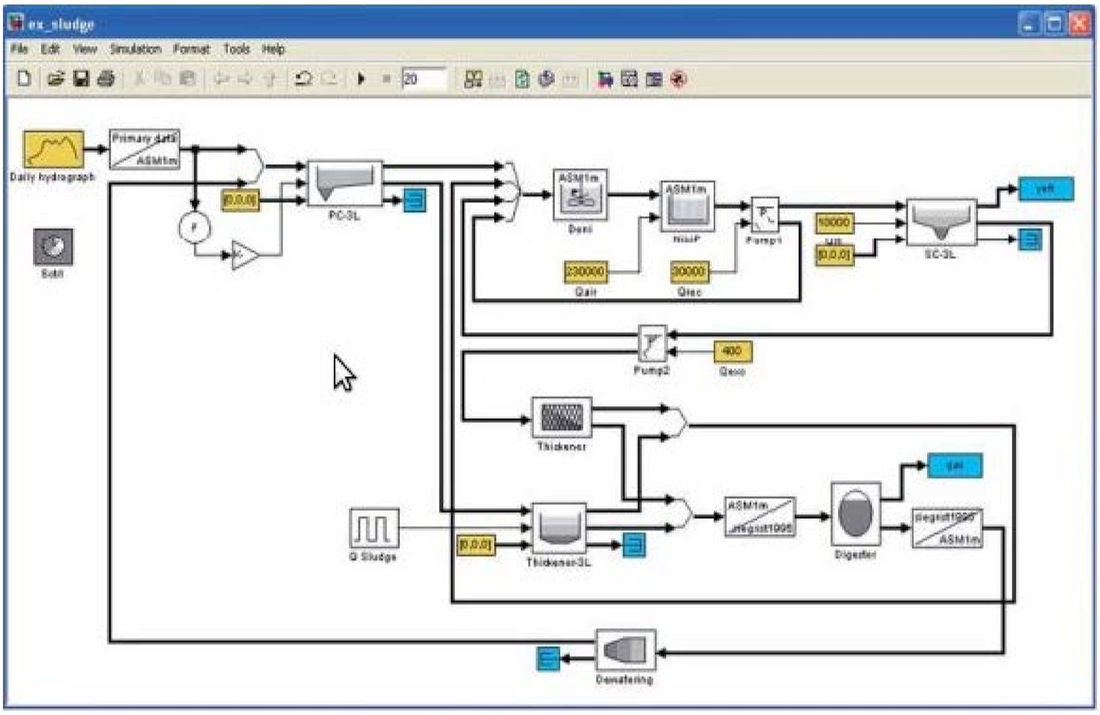


Figure 3.10 SIMBA model of wastewater treatment plant

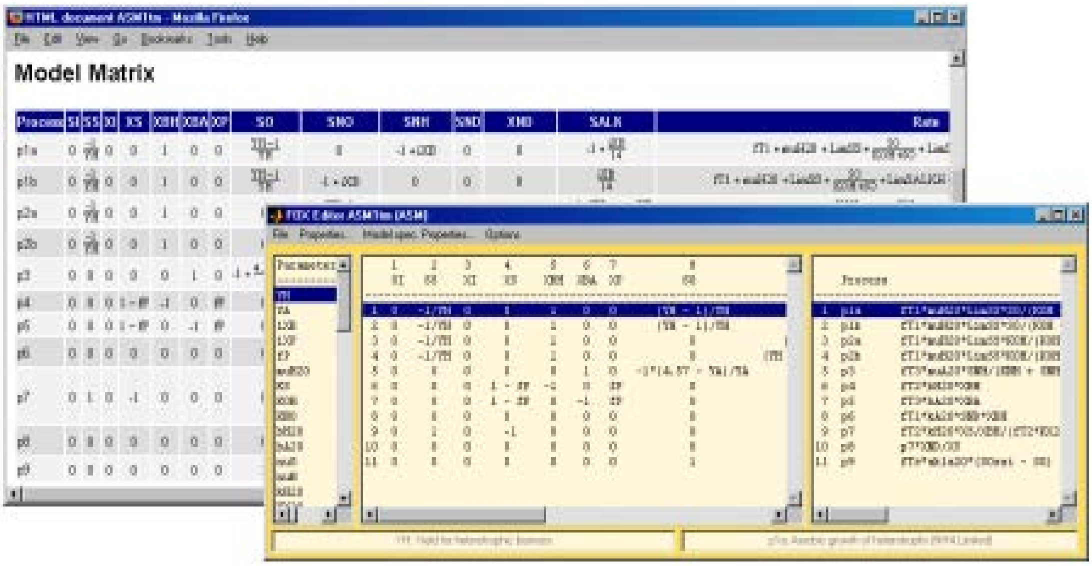


Figure 3.11 Model editor and HTML document (ASM1)

“For the future applications, this property is important for the exchange and standardization of models. Hence, using SIMBA allows the uniform definition and simulation of biochemical models for activated sludge processes, sludge digestion processes and process in receiving waters. Particularly, examination of control strategies can be carried out. This is also possible for the total system consisting of sewer system, wastewater treatment plant and receiving water" (Retrieved from the http://www.ifak.eu).

In a similar way, also river water quality modeling is possible, thus making SIMBA suitable for studies involving integrated simulation and control (Schütze et al., 2002).

3.7 ASIM

Schütze et al. are reported that "ASIM (Activated Sludge Simulation Program) is a simulation program, which allows for the simulation of a variety of different biological wastewater treatment system was developed by the Swiss Federal Institute for EAWAG (Environment Science and Technology). With the program only activated sludge process can be modeled and it does not contain any module for primary clarification. But, it can be built using the reactor building blocks with very simple models" (Schütze et al., 2002; Retrieved from http://www.asim.eawag.ch).

The original version of ASIM only allows for a limited time steps to be simulated. Activated sludge systems with up to 10 different reactors in series (aerobic, anoxic, anaerobic), including sludge return and internal recirculation streams, batch reactors, etc.

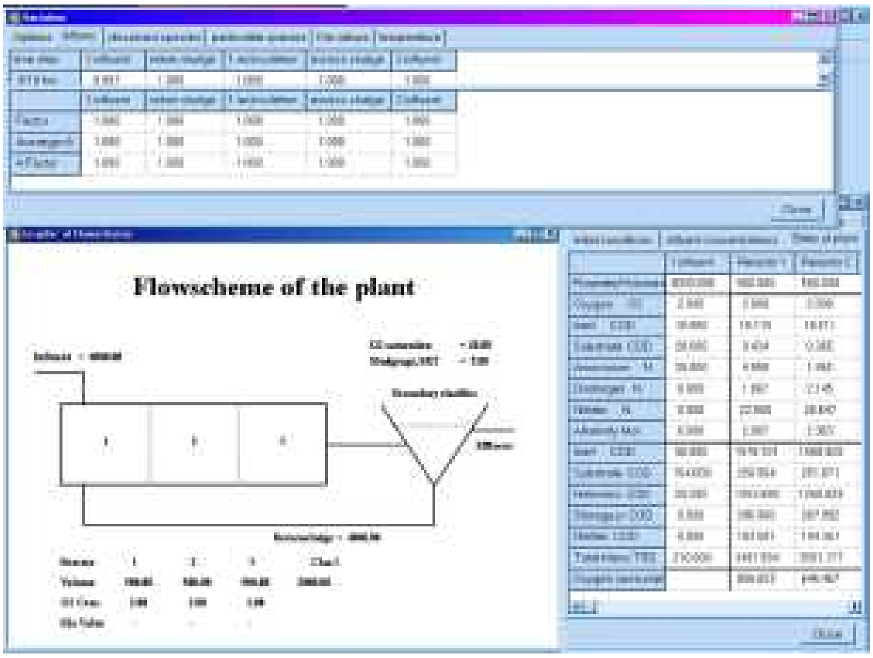


Figure 3.12 The interface of the ASIM

It is indicated that “A menu driven user interface with context sensitive help information (Figure 3.12), graphic support and simple file handling makes the program easy to use in class rooms, research and commercial applications” (Retrieved from http://www.asim.eawag.ch). The futures of the program:

- Analysis of the actual state
- Dynamic modeling
- Determination of load limits
- Simulation of specific operation conditions
- Examination of spare capacity
- Elaboration of control concepts
- Plant optimization

Figure 3.13 The interface of the ASIM

It is specified that “The special of the feature of ASIM is that biokinetic models (the different materials or components used to characterize the wastewater and the transformation processes with relevant stoichiometry and kinetics) may be independently defined, stored and edited by the user. A variety of the biokinetic models is also supplied with the program (with/without nitrification, denitrification, and phosphorus removal). This allows the researcher to develop his own specific model. Simple as well as complex models are distributed together with the program in the model library. Also model similar to the IAWPRC Activated Sludge Models No: 1 (adapted), No: 2 are implemented” (Retrieved from http://www.asim.eawag.ch).

CHAPTER FOUR
MBR SYSTEM DESIGN METHOD APPLIED IN THIS STUDY

4.1 Introduction

Especially in recent years MBR technology has been widely applied for the various industrial and municipal wastewater treatment plants and the appropriate design of MBR system is becoming more important issue for the environmental engineers. There are some MS-Excel based design programs presented by various manufacturers such as KUBATO, TORAY, etc. and these programs can be used to design MBR facilities for very wide applications.

In general the design process consists of three phases:

- 1st Phase is related to the selection and operation of the pretreatment processes
- 2nd Phase is related to the sizing of MBR tank and the mechanical design of the membrane system
- 3rd Phase is related to the needed volume for biological reactor

In the scope of this study, MBR system design was accomplished considering these phases. As mentioned in the previous sections, the pretreatment should be designed and selected according to recommendations of manufacturers for ensuring effective pretreatment towards to polluting materials which may blocked the module or damage the membrane.

At the beginning of the calculation of MBR tank dimensions studies, the raw wastewater quantity and sludge quality in the MBR basin according to operational conditions was accepted. Then the required membrane surface was determined and the dimensions of the MBR tank were calculated considering the required surface area and specified plant configuration (can be change according to site specific requirements and needs). In addition, the scouring air flowrate/coarse air blowers, required pump capacity for permeate, and recirculation rate were also determined on this phase.

The bioreactor was designed for municipal wastewater including small amount of industrial wastewater and all calculations were made according to the ATV A131E. According to the accepted pollution loads, target effluent quality, and specified the configuration of biological treatment, the volume of the bioreactor and oxygen demand were calculated.

4.2 Process Design

Typical procedure for the design of MBR process for municipal wastewater treatment plant is shown below, step by step.

4.2.1 Design of Membrane Filtration Process

Design of Membrane Filtration Process involves the following steps:

- Net flux calculations
- Type of membrane
- Required membrane
- Required aeration

An important parameter in designing of MBR is flux value and depending on the temperature, this value is necessary to determine the total effective required surface area. While it is possible to work with a very high flux values in municipal wastewater, lower flux values are needed for industrial wastewater. However it should be noted that each industrial facility may differ from each other and therefore the characteristics of wastewater can be different. So, a pilot test is usually required to determine the appropriate flux for the real industrial wastewater.

The flux value can be calculated by the following formula;

$Flux\ (l/m^2.h) = [Flow\ (m^3/h)\ x\ 10^3]\ /\ [Membrane\ Area\ (m^2)]$

In this study, it was decided to use TORAY membranes. Figure 4.1 shows the relationship between the temperature and flux and the typical flux values of TORAY membranes for the different applications are given in Table 4.1.

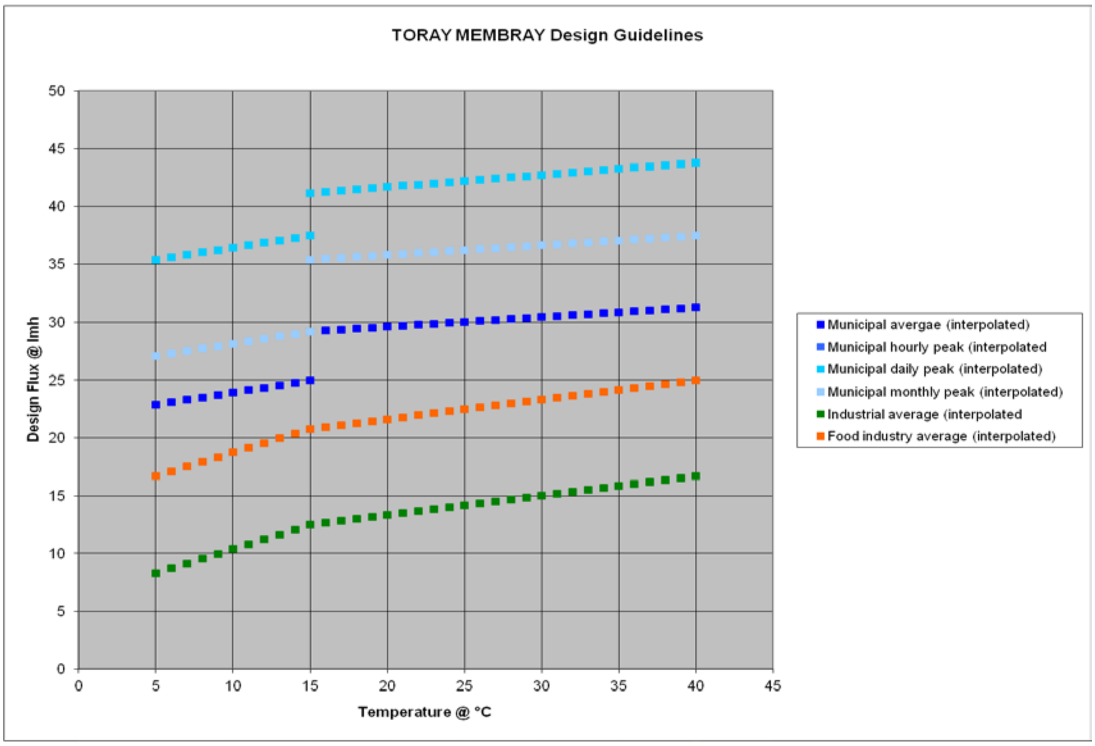


Figure 4.1 The relationship between temperature and flux

Table 4.1 The typical flux values for the different applications

Application (MLSS: 8 – 15 g/L)		Daily average	Daily Peak max. duration, 24 h	Monthly Peak max. duration, 7 d
Municipal	< 15°C	< 21 L/m^2.h	< 31.5 L/m^2.h	<24.5 L/m^2.h
	> 15°C	< 26.5 L/m^2.h	< 37.0 L/m^2.h	< 31.5 L/m^2.h
Food Industry	< 15°C	< 17.5 L/m^2.h	**not available**	
	> 15°C	< 21 L/m^2.h		
Industry	< 15°C	< 10.5 L/m^2.h		
	> 15°C	< 14.0 L/m^2.h		

Since the wastewater type is the key factor for the determination of flux, firstly it should be determined as sewage municipal wastewater.

After the total required membrane surface area is determined by the values of the flux, the design type of MBR system is determined. In this study, both integrated (internal) and separate (external) MBR system design configuration was examined, separately. The integrated MBR systems are generally used for small or containerized plants, whereas the standard concept for the combination of the biological and the membrane processes should be a separated system. Nevertheless, it will be able to possible to see the effect of both separation mechanisms on the system design in this study.

Flow rate is one of the most significant parameter for the calculation of the required membrane surface area. In this study, it was selected as representing the settlement of a population of less than 10,000 and the maximum daily flow rate of 1,200 m^3/d was chosen.

- Max. Daily Capacity : 1,200 m^3/day
- Continuous Operating Flow Rate : 50 m^3/h

However, it is an important point to keep in mind that peak flow rate should be used for determining the required quantity of membrane modules. The duration of all peak flows should be defined before designing the MBR process. So, as a peak flow rate of 1,200 m^3/d was chosen. The system should be capable to treat wastewater at the peak flow rate.

The application of flow equalization prior to the MBR enhances the stability of the operation, allowing the system to operate at a more constant flux as well as minimizing the potential of exceeding design flux during peak periods (e.g. storm water events) or interrupting operation during low or no flow periods (typically seen in weekend of industrial waste water treatment plant). These features of equalization will result in a more compact MBR design, longer membrane life and less membrane fouling (Toray Engineering Manuel, 2009).

According to the studies, the MLSS in the MBR tank should be between 7 - 18 g/L during the operation (Coppen, 2004; AMTA, 2007). Generally, the recommended value for MLSS is 15 g/L. In this study, different MLSS concentrations in the range of 7 - 20 g/L were examined to determine the optimum value for both separated system and integrated system.

In membrane systems, temperature affects the amount of flux directly. Because viscosity tends to decrease with increasing temperature, flux is getting higher at high temperatures. Therefore, it would be difficult to obtain an effective result if the lowest temperature is not taken into account during the designing stage. Optimum temperature range changes depending on the membrane type. TORAY recommends that the temperature should be the range of 5 and 40 °C. The viscosity of the sludge should be lower than 250 mPa.s. The dissolved oxygen (DO) concentration of the outlet of the biological tank (nitrification zone) should be higher than 1 mg/L.

The following MLSS values and other important parameters, such as temperature, viscosity, DO, and pH were selected as design parameters for the MBR basin sludge quality:

- MLSS : 7, 10, 12, 15, 18, 20 g/L
- Temperature : 15 °C
- Viscosity : < 250 mPas.s
- DO : > 1 mg/L
- pH : 7

Membrane surface area can be estimated from the following formula by determining the peak flow (Q_p) and peak flux value (J_p) and, it must be checked for average flow and average flux must be checked.

$$\begin{aligned} \textit{Needed Membrane Surface Area } (m^2) &= Q_p\ (m^3/h) \,/\, J_p\ (l/m^2.h) \\ &= 50\ (m^3/h) \,/\, 24.8\ (l/m^2.h) \times 1000\ (l/m^3) \\ &= \mathbf{2.016\ m^2} \end{aligned}$$

According to the Figure 4.1, the value of flux was selected as 24.8 L/m^2.h for municipal wastewater at the design temperature of 15 °C. Consequently, the required membrane area was calculated as 2,016 m^2 from the above formula. The type and amounts of membrane module was chosen depending on the required membrane surface area.

The module specification of TORAY TMR140 Series is given in Table 4.2. There are three possible TORAY TMR140 modules:

- Small capacity with a single train of TMR140-100S modules
- Medium capacity with two trains of TMR140-200W
- Large capacity with four trains of TMR140-200D

Table 4.2 The module specification of TORAY TMR140 Series

Module Type		**TMR140-100S**	**TMR140-200W**	**TMR140-200D (Double Deck)**
Elements		TSP 50150		
Number of Elements		100	200	200
Membrane Area, m^2		140	280	280
Standard Conditions Permeate Flow m^3/d.module (T > 15°C, TSS<1.0 mg/L, Turbidity < 1.0 NTU)		105	210	210
		approx. 31 L/m^2.h		
Scouring Air Flow rate, NL/min.module		1,300 – 2,000	2,600 – 4,000	1,800 – 2,000
Dimensions	Width, mm	810	840	810
	Length, mm	1,620	3,260	1,620
	Height, mm	2,100	2,100	4,160
Weight (dry), kg		695	1,430	1,365
Material	Frame	304 SS or 316SS		
	Permeate Manifold	304 SS or 316SS		
	Diffuser	304 SS or 316SS		

In this study, TORAY TMR140-200D module was chosen. The overview of TORAY TMR140-200D module is given in Figure 4.2.

Figure 4.2 The overview of TORAY TMR140-200D module (Retrieved from http://www.toraywater.com/products/mbr/catalog/tmr140_200d.html)

This type module is generally used for large size applications where needed water level higher than 4.7 m and it has highest efficiency of scouring aeration, even more importantly is needed lowest footprint.

TMR 140 series modules manufactured by TORAY are a module composed of an element block an aeration block (Figure 4.3). TMR 140-200D modules consists placed on top of two units of TMR140-100S. The element blocks contains 200 number of membrane elements stacked at equal intervals, each of which has flat sheet membranes attached on both sides of a supporting panel. Each element connected via a tube to a filtered effluent manifold. The aeration block is a matching unit containing a coarse bubble diffusers used to supply air as shown in Figure 4.3. The aeration block supports the element block and directs the mixture of air bubbles and mixed liquid between the membrane elements in the element block.

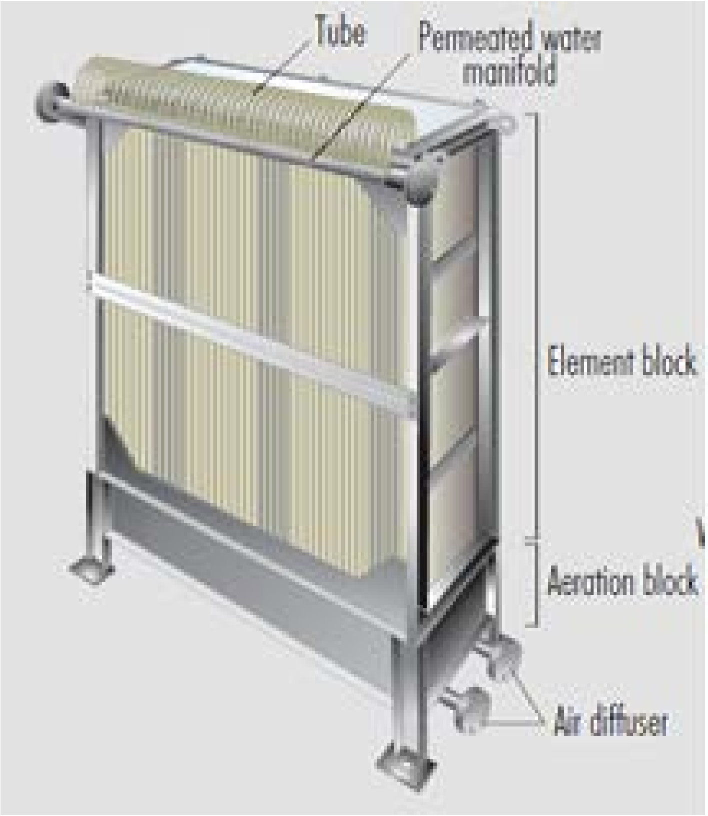
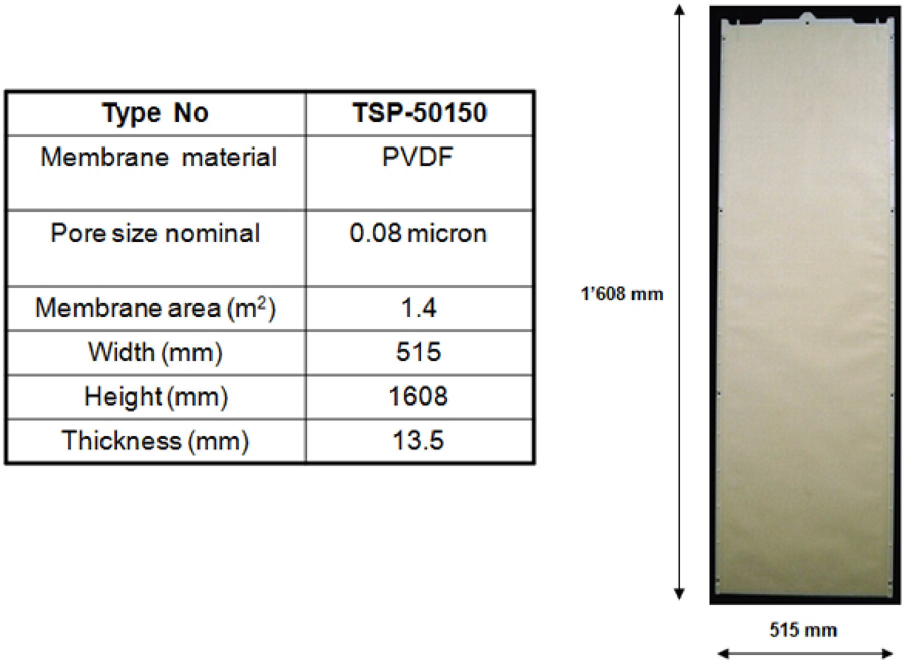


Figure 4.3 Appearance of membrane module (Retrieved from http://www.toraywater.com/products/mbr/TMR140_series.pdf)

Toray uses a flat sheet membrane made of PVDF (Polyvinylidene Fluoride) with non-woven cloth base giving a nominal pore size of 0.08 µm. The membrane element filtered activated sludge passes through to the interior of each membrane element to an outlet pipe into the top of the support plate. Each membrane element provides an effective filtration area of 1.4 m^2.

The element is of a simple flat sheet membrane construction as shown in Figure 4.4.



Type No	TSP-50150
Membrane material	PVDF
Pore size nominal	0.08 micron
Membrane area (m^2)	1.4
Width (mm)	515
Height (mm)	1608
Thickness (mm)	13.5

Figure 4.4 Structure of element (Retrieved from http://www.varmo.com/en/modules-membrane-submerged-mbr)

The PVDF (Polyvinylidene Fluoride) as a membrane material makes it more suitable in chemical stability and physical strength, and numerous pore diameters with an average size of 0.08 micron are distributed over the membrane surface with a diameter distribution (Figure 4.5). Due to the nominal pore distribution, it gives a high treated water quality and excellent water permeability.

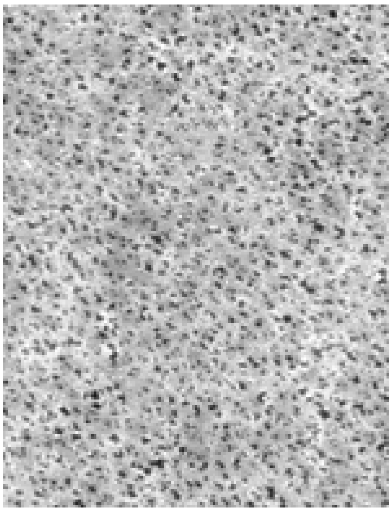


Figure 4.5 The microscopic appearance of PVDF membrane element (Retrieved from http://www.varmo.com/en/modules-membrane-submerged-mbr)

The membrane surface is cleaned effectively by an upward stream of water generated as air is diffused below it (Figure 4.6). The air-water mixture maintains an upward cross flow over the membrane surface, minimizing fouling of the membranes. This mechanism ensures stable filtration because the membrane does not easily admit of sludge adherence to its surface.

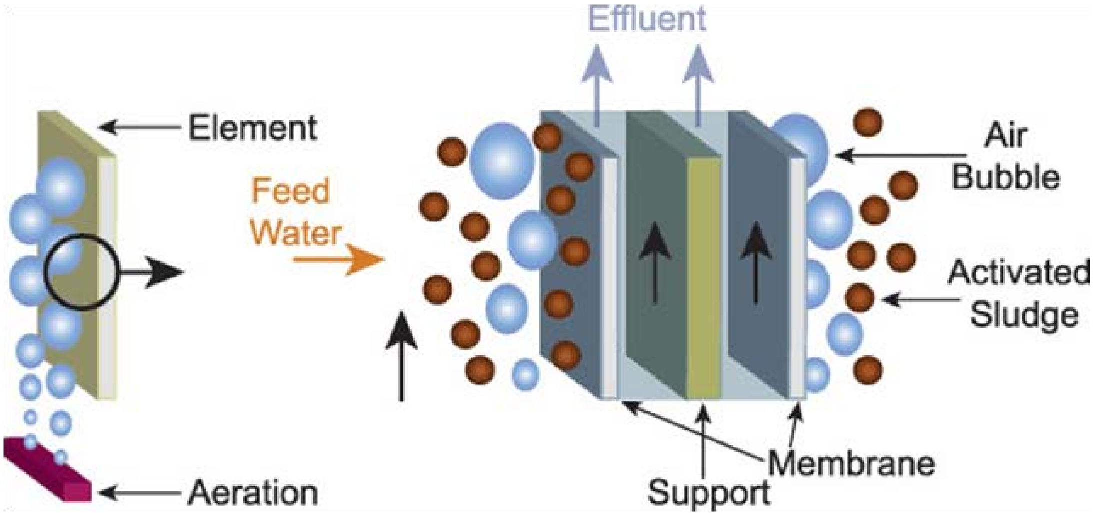


Figure 4.6 Filtration principle of activated sludge (Retrieved from http://www.varmo.com/en/modules-membrane-submerged-mbr)

The number of module can be determined from the following formula by selecting the module size and surface area;

$$\begin{aligned} \textit{Number of Modules} &= \textit{Membrane Area } (m^2) \,/\, \textit{Module Area } (m^2/\textit{module}) \\ &= 2.016\ (m^2) \,/\, 280\ (m^2/\textit{module}) \\ &= \boldsymbol{7.2 \approx 8}\ \textbf{\textit{modules chosen}} \end{aligned}$$

The plant configuration for MBR depends on the size of plant and number of trains. The configuration must be round up to equal number of modules per train.

- Number of Trains : 2 Trains
- Number of Module per Train : 4 Modules per Train

The type of the modules used in a plant should be the same. Different type of module will make the operation more complicated and difficult. The numbers of modules per train and the number of trains per tank should be the same in every train or tank, in order to simplify design, operation and maintenance. In this study, two trains were selected, every train includes four modules as a plant configuration and one tank because of it is not a very large application. But, more than two MBR tanks design enables regular replacement without stopping the whole plant in order to allow for one of the tanks to be taken out of operation.

The needed surface area was calculated as 2.016 m^2 and accordingly the number of installed module was achieved as 7.2 module, however we chosen as 8 module. So, If we re-calculate the installed membrane area:

$$\begin{aligned} \textit{Inst. Memb. Area}(m^2) &= \textit{No of Mod.} * \textit{Memb. Area Per Mod.}(m^2/\textit{module}) \\ &= 8\ \textit{module} * 280\ m^2/\textit{module} \\ &= \boldsymbol{2.240\ m^2} \end{aligned}$$

According to this result, the continuous flux value should be re-calculated because of the installed membrane area changed. The results are also given in Table 4.3.

$$\mathit{Continuous\ Flux}\ (l/m^2.h) = [\mathit{Flow}\ (m^3/h) \times 10^3] / [\mathit{Membrane\ Area}\ (m^2)]$$

$$= [50\ m^3/h * 10^3] / [2.240\ m^2]$$

$$= \mathbf{22.3\ l/m^2.h}$$

Table 4.3 Installed average flux

Operation Condition	**Unit**	**Normal**	**Design Guideline**
Number of modules	module	8	15 °C
Installed Membrane Area	m^2	2240	
Continuous	$L/m^2.h$	22.3	24.8
Hourly peak (< 1h)	$L/m^2.h$	-	35.0
Daily peak (< 24h)	$L/m^2.h$	-	35.0
Monthly peak (< 30days)	$L/m^2.h$	-	30.1

According to calculations, the value of continuous flux is 22.3 $L/m^2.h$. If the flux in one of the cases is higher than the allowed design flux (24.8 $L/m^2.h$), the number of modules has to be increased.

As mentioned in the previous sections, two kinds of the filtration patterns are available. One is the simple continuous filtration and the other is the filtration with relaxation that is the intermittent filtration. In the case of the intermittent filtration, the filtration is relaxed for a short period at certain intervals while the air scouring continues, as shown in Figure 4.7. In this way, while the filtration is suspended, the membrane surface is cleaned up more effectively with the scouring air due to the absence of suction. Time chart for intermittent filtration is given in Table 4.4. The recommended time cycle for the intermittent filtration is 9-minute filtration and 1-minute relaxation. Longer relaxation could be helpful if there is a tendency of cake formation. The scouring air is on all the time, if the modules are in the operation.

Figure 4.7 Recommended time chart for intermittent filtration (Toray Engineering Manuel, 2009)

Table 4.4 Time chart for intermittent filtration

	Filtration	**Relaxation**	**Total**
Filtration	9 minute	1 minute	10 minute
Air Diffusion	Continuous		

For continuously cleaning of the membrane, the scouring air is important. Table 4.5 shows the required air flow for membrane scouring; this calculation does not consider oxygen demand for biological treatment.

Table 4.5 The scouring air flow rate/coarse air blower

	Unit	**Min**	**Max**	**Recommended**
Required Scouring Air	m^3/h.module	78	120	90
Required Scouring Air per Train	m^3/h.module	312	480	360
Total Scouring Air	m^3/h	624	960	720
Blower Feed Pressure	520 mbar + aeration piping head loss			
Permeate Extraction	Gravity Mode (min. 3 m hydrostatic pressure needed; no permeate suction pump needed)			

There are two options for the membrane filtration process. One is for the filtration with natural head and other is with suction pump. The schematic flow diagrams of the membrane filtration process are shown below.

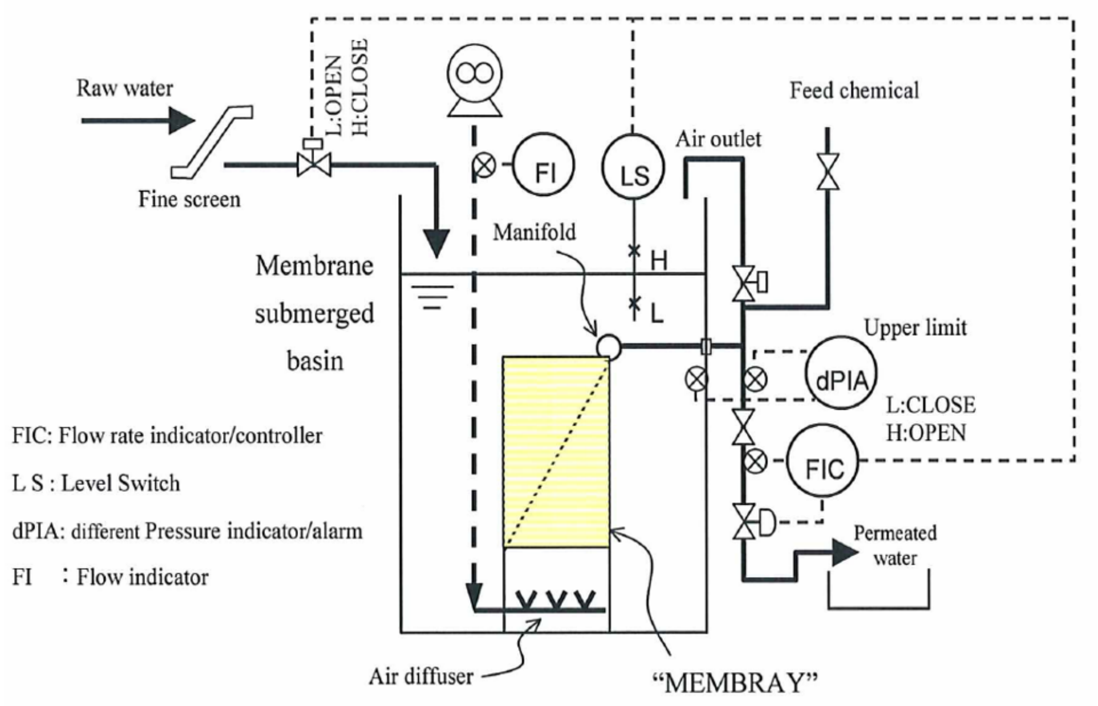


Figure 4.8 Natural water head operation (Toray Engineering Manuel, 2009)

The filtration can be performed with using a natural water head differential pressure generated from a vertical distance between the liquid level of the membrane submerged tank and the level of the permeate water outlet (Figure 4.8). In order to obtain enough suction pressure for the filtration, the permeate water outlet should be located enough below the liquid level of the membrane submerged tank (normally located at the same level as the bottom of the element block).

TORAY recommended that in gravity filtration, the air accumulated in the permeate water line should be discharged once a day at least; otherwise the effective water head is reduced seriously.

In this case that filtration with suction pump; filtration is controlled by a suction pump with an automatic control valve (Figure 4.9). The suction pump is automatically activated depending on the water level in membrane basin. Especially in such configuration, equalization tank has an important factor in order to minimize fluctuations.

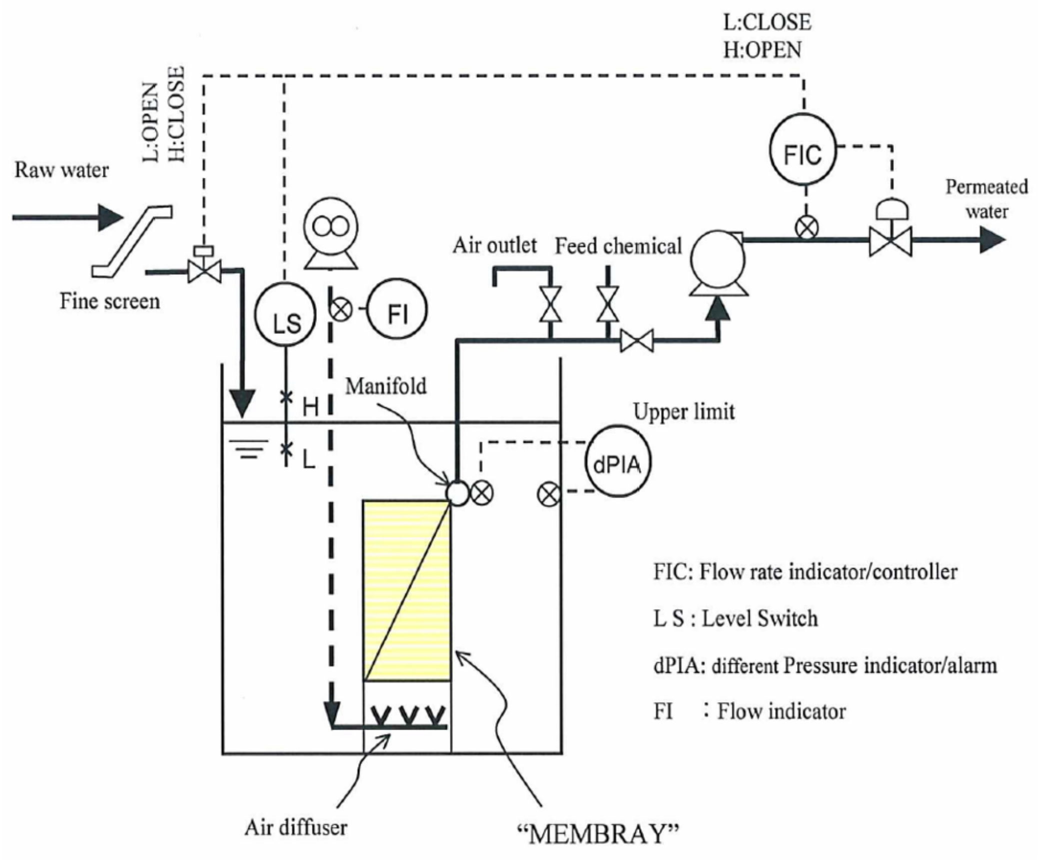


Figure 4.9 Pump section operation (Toray Engineering Manuel, 2009)

In this study, gravity mode permeate extraction was selected; however it does not cause any change selecting any configuration such suction pump. This is only relevant with configuration.

Toray has suggested in the range of 8-12 g/L MLSS concentration in the biological tank. So, a lower efficiency of the biological aeration at MLSS concentration ($\geq$ 12 g/L) must be considered. The recirculation is needed to achieve high bacterial concentration (MLSS) in the biological tank. Table 4.6 shows common MLSS concentrations in the MBR/biological tank and typical recirculation rates depending on the TORAY design. The MLSS concentration of the biological reactors to be same with membrane tank and the recirculation rate is not active if an integrated system in selected.

Table 4.6 MLSS and Recirculation Rate

Parameter	Typical Value	Design Recommendation
MLSS in MBR Tank	7 - 18 g/L	15 g/L
MLSS in Biological Tank	5 - 12 g/L	10 g/L
Recirculation Rate	100 - 500 % of daily capacity	200 %

The MLSS in the biological tank can be calculated as:

$$MLSS_{bio} = (MLSS_{MBR} \times r)/(1+r)$$

where;

$MLSS_{bio}$ = Sludge concentration in biological tank (g/L)

$MLSS_{MBR}$ = Sludge concentration in MBR tank (g/L)

r = Recirculation rate

The above formula indicates that a lower recirculation rate will result in a greater difference between the MLSS in the biological tank and the MLSS in the MBR tank, which means lower MLSS in the biological tank or higher MLSS in the MBR tank. To avoid possible filtration trouble caused by too concentrated sludge in the MBR tank, enough recirculation flow has to be designed.

There are two possibilities to feed the MBR tank / recycle the sludge from the MBR to the biological tank:

a) **Gravity:** The sludge flows by gravity into the MBR tank and is pumped back into the biological section (Figure 4.10).

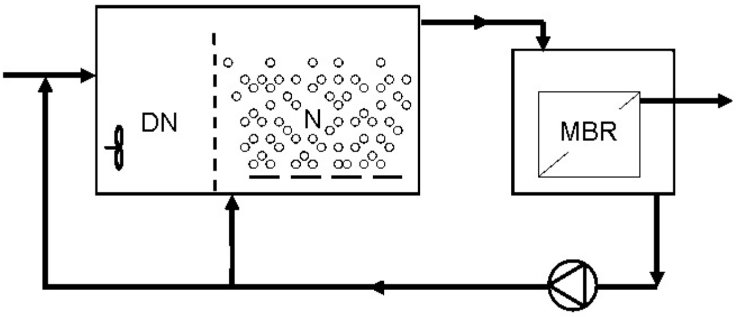


Figure 4.10 Recirculation by feed pump (Toray Engineering Manuel, 2009)

b) Pumping: In case of the MBR levels is higher than the level in the biological tank, the feed of the MBR tank is by pumping and the recirculation by gravity flow (Figure 4.11).

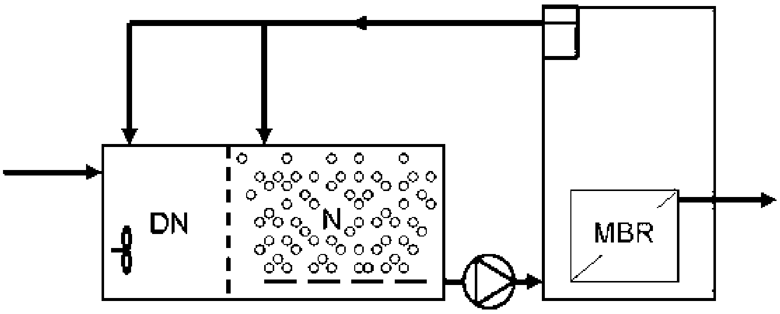


Figure 4.11 MBR feed by pump (Toray Engineering Manuel, 2009)

The sludge recirculation is only needed for separated filtration design. The tanks of the integrated design should be total intermixed and MLSS is nearly constant in the whole tank. In case using the pump for biomass recirculation, the feed/recirculation pump capacity is calculated from the following formula:

$$\text{Total Feed/Recirculation Pump } (m^3/h) = Q_h\ (m^3/h) \times \text{Recirculation Rate } (\%) / 100$$

The pump capacity is calculated according to the recirculation rate. For instance, if the recirculation rate is taken 200 %, the following result from the above formula is achieved:

- Biomass Recirculation : by Feed Pump
- Recirculation Rate : 200 %
- Total Feed/Recirculation Pump Capacity : 100 m^3/h.tank
- Required Pump Capacity per Train : 50 m^3/h.train

Because of the recirculation flow is highly aerated with oxygen, the recycled sludge that includes high oxygen could affect the denitrification reactions. This is usually a negative situation for existing applications. In order to protect the system, a part of the recirculation flow should be pumped in to the nitrification tank as shown in Figure 4.12 and this rate should be considered depending on the treatment requirements.

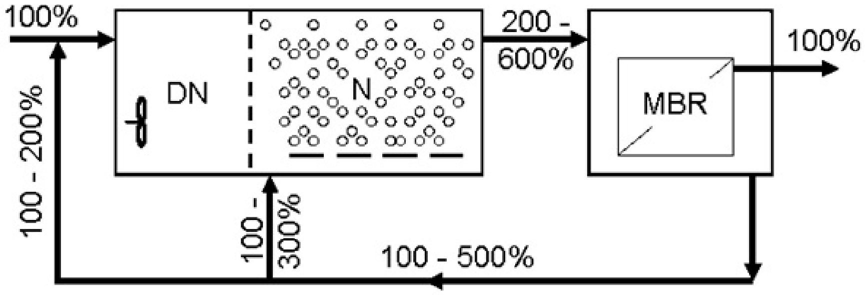


Figure 4.12 General recirculation scheme (Toray Engineering Manuel, 2009)

The accepted tank dimension does not consider the needed space for pipe work, installation, etc. Detailed engineering is needed to decide the tank dimensions. The water level varies depending on the selected membrane module. However, there is an issue that should be taken into consideration is the freeboard level should be at least 50 cm. The biological active tank volume could consider as biological active volume especially for nitrification.

Tank Design with TMR140-200D Module

The modules should be placed in the tank according to membrane manufacturer's requirements for distances between module/tank walls, module/module units as illustrated in Figure 4.13 and Figure 4.14 presents a side view and a top view of the tank.

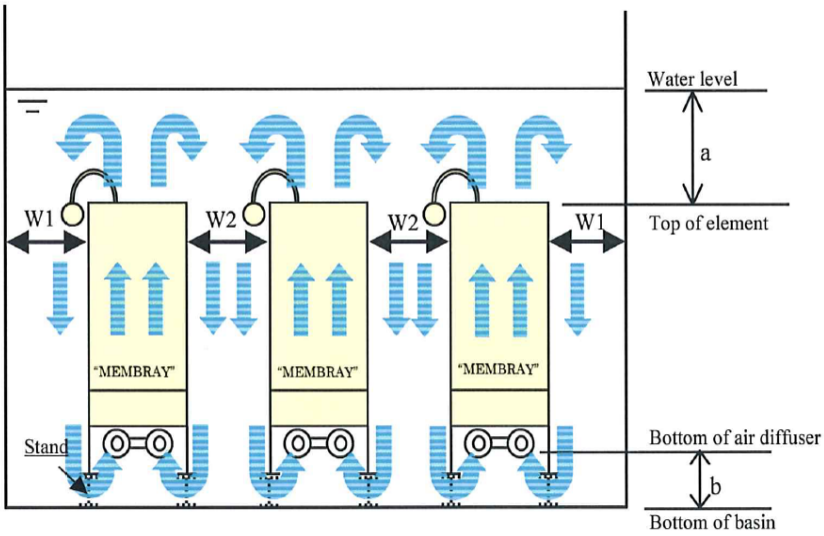


Figure 4.13 Module layout in membrane submerged tank (Side View)

*a, the distance between the liquid level of membrane tank and the top of surface of the membrane module should not be less than 500 mm during the operation.

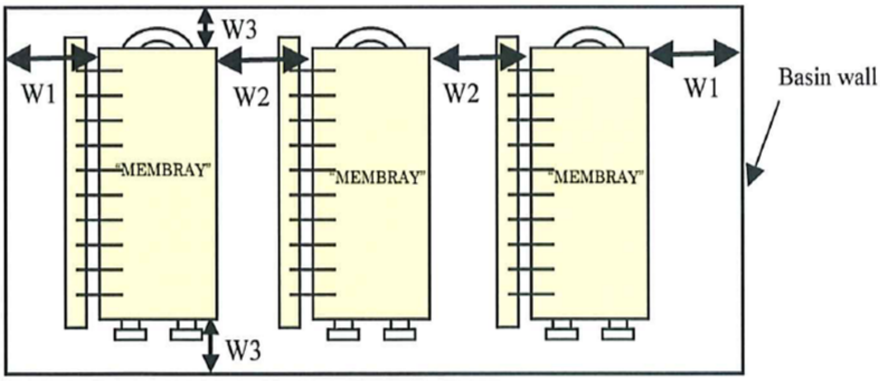


Figure 4.14 Module layout in membrane submerged tank (Plan)

It is very important to arrange the membrane modules with appropriate distances in order to obtain an effective circulation flow. It is required to keep the dimension of W1, W2, W3, and “a” as mentioned in Table 4.7.

Table 4.7 Tank distance

	Minimum	**Maximum**	**Unit**
Basin wall to module frame (W1)	380	680	mm
Module frame to frame (W2)	430	730	mm
Train to train (W3)	400	400	mm

* W3 should be as short as possible (normally about 400 mm) within the range allowing piping and maintenance work

According to these requirements the tank dimensions were calculated by the following formulas:

Water Level = Module Height + a
= 4160 mm + 500 mm
= 4660 mm = 4.66 m (Minimal Water Depth)
= **4.80 m** (Chosen)

Basin Depth (H) = Water Level + Freeboard
= 4.80 m + 0.50 m
= 5.30 m **≈ 5.50 m**

In this study two trains were chosen for MBR tank and the number of modules per trains is four.

- Number of Trains (t) = 2 trains
- Number of Modules per Train (n) = 4 modules

Min. Basin Length (L_{min}) = [2*$W1_{min}$+(n-1)*$W2_{min}$ +n*Module Width]/1000
= [2*380mm+(4-1)*430mm+4*565mm]/1000
= 4310 mm
= 4.31 m

Max. Basin Length (L_{max}) = [2*$W1_{max}$+(n-1)*$W2_{max}$ + n*Module Width]/1000
= [2*680mm+(4-1)*730mm+4*565mm]/1000
= 5810 mm
= 5.81 m

Chosen Basin Length (L) **= 5.50 m**

Min. Basin Width (W_{min}) = [2*$W3_{min}$+t*Module Length+(t-1)*$W3_{min}$ *2]/1000
= [2*400mm+2*1460mm+(2-1)*400mm*2]/1000
= 4.52 m

Max. Basin Width (W_{max}) = [2*$W3_{max}$+t*Module Length+(t-1)*$W3_{max}$*2]/1000
= [2*400mm+2*1460mm+(2-1)*400mm*2]/1000
= 4.52 m

Chosen Basin Width (W) **= 5.00 m**

MBR Tank Volume (V_{MBR}) = W*L*H
= 5.00m*5.50m*5.50m
= **151.25 m^3**

The selected and calculated tank dimensions are summarized in Table 4.8.

Table 4.8 Tank dimensions

Number of Trains per Basin	2	Trains	
Number of Module per Train	4	Modules	
Number of Installed Modules	8	Modules	
Number of MBR Tank	1	Tank	
	Min.	**Assumed**	**Chosen**
Water Level (m)	4.80	4.80	-
Freeboard (m)	0.50	0.50	-
Basin Depth (m)	5.30	5.30	5.50
Basin Length (m)	4.31	5.81	5.50
Basin Width (m)	4.52	4.52	5.00
MBR Tank Volume (m^3)	-	-	151.25

A plant configuration with TMR140-200D modules is the most competitive solution for large scale configurations and if a water level of more than 4.7 m is available. The most important feature of this type of module configurations, it is owing to the low scouring air demand and small footprint per membrane area (Figure 4.15).

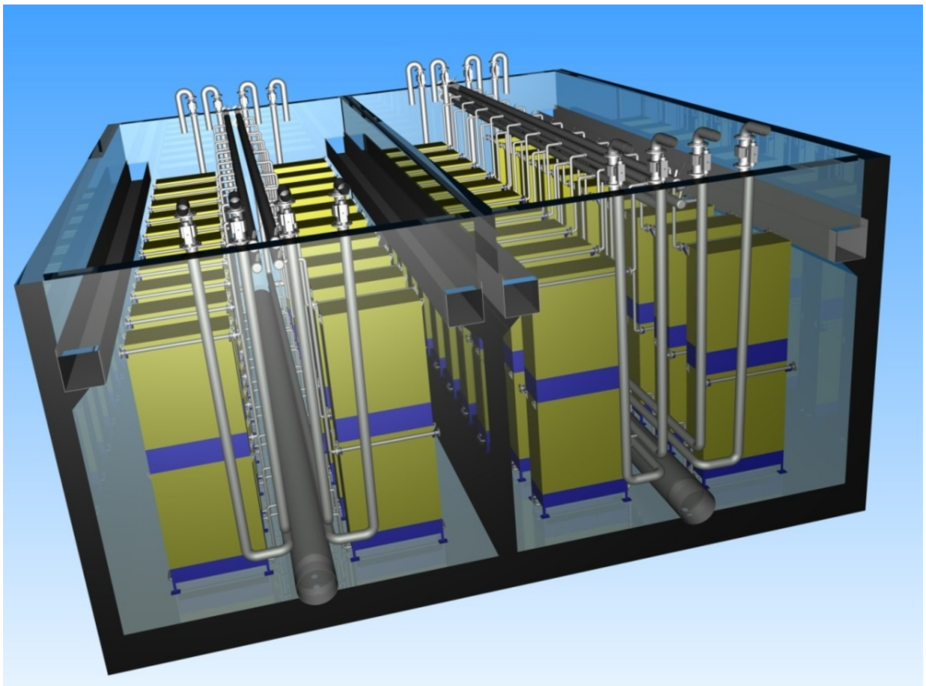


Figure 4.15 TMR140-200D module configuration (Toray Engineering Manuel, 2009)

The standard operating conditions are shown in Table 4.9.

Table 4.9 The standard operating conditions

Parameter	Unit	Operating conditions
MLSS	g/L	7.0 – 15.0 (max. 18.0)
Sludge Viscosity	mPa.s	<250
Dissolved Oxygen	mg/L	>1.0
pH	-	5 – 10
Temperature	°C	5 – 40
Continuous filtration flux	L/m^2.h	8 – 25
Scouring Air	NL/min. element	13 – 20 (9 – 10 in case of TMR140-200D)
Typical TMP	mbar	50 – 100

4.2.2 Bioreactor Design

Bioreactor design is carried out according to ATV A131E. MBR treatment plant with activated sludge system is completely based on advanced wastewater treatment performance.

For advanced wastewater treatment, the typical Nitrification/Denitrification process is:

- Alternate usage of tanks with changing oxygen conditions
- Change oxygen conditions in one tank for Intermittent Nitrification/Denitrification
- Rapid repeating change of oxygen conditions for Simultaneous Nitrification/Denitrification
- Denitrification upstream of Nitrification is widely used and is possible only with recirculation of nitrate

In this study, nitrogen and phosphorus removal was taken into consideration for bioreactor design. Simultaneous/Intermittent Denitrification process and upstream Anaerobic Tanks with no chemical addition was selected for denitrification and for Bio-P removal, respectively. The average daily flow rate of 1,200 m^3/d was accepted and the properties of wastewater after pre-treatment were accepted as given in Table 4.10:

Table 4.10 The accepted properties of influent pre-treated wastewater

Parameter	**Unit**	**Influent Value**
Q_{day} (Daily average flow rate)	m^3/d	1200
Q_{hour} (Hourly average flow rate)	m^3/h	50
BOD_5 (Biological oxygen demand)	mg/L	300
COD (Chemical oxygen demand)	mg/L	500
TKN (Total Kjeldahl Nitrogen)	mg/L	50
NH_4-N (Ammonium as Nitrogen)	mg/L	35
Norg-N (Organic Nitrogen)	mg/L	15
Ptot (Total Phosphate)	mg/L	5
SS (Suspended Solid)	mg/L	300

The desired effluent quality is very important for biological treatment process and the targeted effluent quality is specified in Table 4.11.

Table 4.11 The effluent water quality

Parameter	**Unit**	**Effluent Value**
BOD_5 (Biological oxygen demand)	mg/L	5
COD (Chemical oxygen demand)	mg/L	20
TKN (Total Kjeldahl Nitrogen)	mg/L	10
NH_4-N (Ammonium as Nitrogen)	mg/L	10
P_{tot} (Total Phosphate)	mg/L	5
SS (Suspended Solid)	mg/L	2

In this study, the effect of the different MLSS, SRT and recycle ratio values on the volume of the reactors and dissolved oxygen consumption were investigated according to both integrated and separated system respectively. The results were calculated using the formulas specified in the ATV A131E and will be discussed in Chapter 5.

Plants with Nitrification and Denitrification (ATV A131E/chapter 5.2.1.3)

The minimum required SRT value calculated according to ATV A131E (chapter 5.2.1.3). The dimensioning sludge age for nitrification and denitrification are calculated from the following formula:

$$t_{ss,aerob,dim} = t_{ss,aerob}*1/[1-(V_D/V_{AT})] \qquad (4.1)$$

According to the ATV A131E (chapter 5.2.1.2), the aerobic dimensioning sludge age to be maintained for nitrification is:

$$t_{ss,aerob} = SF*3.4*1.103^{(15-T)} \qquad (4.2)$$

and with Equation 4-2 the minimum required sludge age calculated from to the following formula:

$$t_{ss,aerob,dim} = SF*3.4*1.103^{(15-T)} *1/[1-(V_D/V_{AT})] \qquad (4\text{-}3)$$

Where;

$t_{ss,aerob}$: Aerobic sludge age referred to volume of the bioreactor used for nitrification

$t_{ss,aerob,dim}$: Aerobic sludge age upon which dimensioning for nitrification is based

V_D/V_T : Volume of the biological reactor used for denitrification

The value of 3.4 is made up from the reciprocal of the maximum growth rate of the ammonia oxidants (nitrosomonas) at 15°C (2.13 d) and a factor of 1.6. Through the latter it is ensured that, with sufficient oxygen that and no other negative influence factors, enough nitrificants can be developed or held in the activated sludge.

Using the safety factor (SF) the following are taken into account;

- Variations of the maximum growth rate caused by certain substances in the wastewater, short-term temperature variations or/and pH shifts
- The mean effluent concentration of the ammonium
- The effect of variations of the influent nitrogen loads on the variations of the effluent ammonia concentration

Based on all experiences it is recommended, for municipal plants with a dimensioning capacity up to $B_{d,BOD}$ = 1200 kg/d (20000 PT), to reckon with SF=1.8 due to the more pronounced influent load fluctuation and for $B_{d,BOD} > 6000$ kg/d (100000 PT) with SF=1.45 (SF : Safety factor for nitrification, $B_{d,BOD}$: The organic loading).

Determination of the Proportion of the Reactor Volume for Den. (ATV A131E/chapter 5.2.2)

V_D/V_{AT} is the volume of the biological reactor used for denitrification calculated according to the ATV A131E (chapter 5.2.2). For designing of nitrogen removal systems, denitrified nitrate is, $S_{NO3,D}$ (mg/L):

$$S_{NO3,D} = C_{N,IAT} - S_{orgN,EST} - S_{NH4,EST} - X_{orgN,BM} \quad (4\text{-}4)$$

The influent nitrate concentration ($S_{NO3,IAT}$) is in general, negligibly small. The concentration of organic nitrogen in the effluent can be set as $S_{orgN,EST}$ = 2 mg/L. To be on the safe side the ammonium content in the effluent for dimensioning is, as a rule, assumed as $S_{NH4,EST} = 0$. The nitrogen incorporated in the biomass is taken into account simplified as:

$X_{orgN,BM} = 0.04 - 0.05 * C_{BOD,IAT}$ (4-5)

For simultaneous and intermittent denitrification processes the following calculation of V_D/V_{AT} can be applied from the following formula:

$(S_{NO3,D}/C_{BOD,IAT}) = [(0.75*OU_{C,BOD}) / 2.9]*[V_D/V_{AT}]$(mg N/mg BOD_5) (4-6)

With the relevant BOD_5 of the inflow to the biological reactor one obtains the ratio $S_{NO3,D} / C_{BOD,IAT}$, which gives the necessary denitrification capacity.

Where;

$S_{NO3,D}$: The daily average nitrate concentration

$C_{N,IAT}$: Influent nitrogen concentration

$S_{orgN,EST}$: Organic nitrogen in the effluent

$S_{NO3,EST}$: The relevant effluent concentration of the nitrate

$X_{orgN,BM}$: The nitrogen incorporated in the biomass

The factor 0.75 indicates an overall lower uptake rate of nitrate compared to the uptake rate of dissolved oxygen. $OU_{C,BOD}$ is oxygen uptake for carbon removal referred to BOD_5 to be taken from the Table 4.12 as a result of the calculation of the dimensioning sludge age and the dimensioning temperature (ATV A131E, 2000).

Table 4.12 Specific oxygen consumption $OU_{C,BOD}$ (kg O_2/kg BOD_5), valid for $C_{COD,IAT}/C_{BOD,IAT}$ <= 2.2

T (°C)	**Sludge Age (days)**					
	4	8	10	15	20	25
10	0.85	0.99	1.04	1.13	1.18	1.22
12	0.87	1.02	1.07	1.15	1.21	1.24
15	0.92	1.07	1.12	1.19	1.24	1.27
18	0.96	1.11	1.16	1.23	1.27	1.30
20	0.99	1.14	1.18	1.25	1.29	1.32

For the temperature range from 10 °C to 12 °C the values calculated using the Equation 4-6 are listed in the Table 4.13.

Table 4.13 Standard values for the dimensioning of denitrification for dry weather at temperatures from 10°C to 12°C and common conditions (ATV A131E, 2000).

V_D/V_{AT}	**$S_{NO3,D}/C_{BOD,IAT}$**		
	Pre-anoxic zone denitrification and comparable processes	Simultaneous and intermittent denitrification	Alternating denitrification
0.2	0.11	0.06	0.085
0.3	0.13	0.09	0.11
0.4	0.14	0.12	0.13
0.5	0.15	0.15	0.15

Standard values for the dimensioning of denitrification for dry weather at temperatures from 10°C to 12°C and common conditions are given in Table 4.13. Denitrification volumes smaller than $V_D/V_{AT} = 0.2$ and greater than $V_D/V_{AT} = 0.5$ are not recommended. For temperatures above 12°C the denitrification capacity can be increased by capacity 1% per 1 °C. If the dimensioning or re-calculation takes place on the basis of COD, one can reckon with $S_{NO3,D}/C_{BOD,IAT} = 0.5*[S_{NO3,D}/C_{BOD,IAT}]$.

With the re-calculation for a value of $V_D/V_{AT} = 0.1$ one can reckon with $S_{NO3,D}/C_{BOD,IAT} = 0.03$ for simultaneous and intermittent denitrification. If, by re-calculation a value of $V_D/V_{AT} < 0.1$ is obtained then $S_{NO3,D}/C_{BOD,IAT} = 0$ is to be set. If the required denitrification capacity is larger than $S_{NO3,D}/C_{BOD,IAT} = 0.15$, then a further increase of V_D/V_{AT} is not recommended. It is to be investigated whether a volume reduction or partial by-passing or primary settling tank and/or, if applicable, a separate sludge treatment are conducive to meeting the target. An alternative is to carry out the planning for the addition of external carbon.

Phosphorus Removal (ATV A131E/chapter 5.2.3)

Anaerobic mixing tanks for biological phosphorus removal are to be dimensioned for a minimum contact time of 0.5 to 0.75 hours, referred to the maximum dry weather inflow and the return sludge flow ($Q_{DW,h}$ + Q_{RS}). The degree of the biological phosphorus removal depends, other than on the contact time, to a large extent on the ratio of the concentration of the readily biodegradable organic matter to the concentration of phosphorus. If, in winter, the anaerobic volume is used for denitrification, then during this period a lower biological excess phosphorus removal will establish.

For the determination of the phosphate to be precipitated a phosphorus balance, if necessary for different types of load, is to be drawn up:

$$X_{P,Prec} = C_{P,IAT} - C_{P,EST} - X_{P,BM} - X_{P,BioP} \quad (mg/L) \qquad (4\text{-}7)$$

Where;

$X_{P,Prec}$: Concentration of phosphorus removed by simultaneous precipitation

$C_{P,IAT}$: Concentration of phosphorus in the homogenized sample as P

$X_{P,BM}$: Concentration of phosphorus embedded in the biomass

$X_{P,BioP}$: Concentration of phosphorus removed with biological excess phosphorus removal process

With normal municipal wastewater one can assume the following for the excess biological phosphorus removal ($X_{P,BioP}$):

- $X_{P,BioP}$ = 0.01 to 0.015 $C_{BOD,IAT}$ or 0.005 to 0.007 $C_{COD,IAT}$ respectively with upstream anaerobic tanks.
- If, with lower temperatures, $S_{NO3,EST}$ increases to ≥ 15 mg/L, it can be assumed: $X_{P,BioP}$ = 0.005 to 0.01 $C_{BOD,IAT}$ or 0.0025 to 0.005 $C_{COD,IAT}$ respectively with upstream anaerobic tanks.

Determination of Sludge Production (ATV A131E/chapter 5.2.4)

The sludge produced in an activated sludge plant is made up of organic matter resulting from degradation and stored solid matter as well as sludge resulting from phosphorus removal:

$$SP_d = SP_{d,c} + SP_{d,p} \qquad (4\text{-}8)$$

Where;

SP_d (kg/d) : Daily waste activated sludge production (solids)

$SP_{d,c}$ (kg/d) : Daily sludge production from carbon removal

$SP_{d,p}$ (kg/d) : Daily sludge production from phosphorus removal

Sludge production for biological phosphorus removal is calculated from the following formula:

$$SP_{d,P} = Q_d*(3*X_{P,BioP})/1000 \qquad (4\text{-}9)$$

$$X_{P,BioP} = 0.01 * C_{BOD,IAT} \qquad (4\text{-}10)$$

Sludge production for carbon removal is calculated from the following formula:

$$SP_{d,c} = B_{d,BOD}* \{0.75 + 0.6 * (X_{SS,IAT}/C_{BOD,IAT})-(0.8*0.17*0.75t_{SS}*F_T)/(1+0.17*t_{SS}*F_T)]\} \qquad (4\text{-}11)$$

Assumption of the SVI and the MLSS Concentration (ATV A131E/chapter 5.2.5)

The sludge volume index depends on the composition of the wastewater and the mixing characteristics of the aeration tank. A high fraction of readily biodegradable organic matter, as are contained in some commercial and industrial wastewater, can lead to higher sludge volume indices. If no usable data are available, the values listed in Table 4.14 are recommended for dimensioning taking into account critical operating conditions.

Table 4.14 Standard values for the sludge volume index (ATV A131E, 2000)

Treatment Target	**SVI (L/kg) Industrial/Commercial Wastewater Influence**	
	Favourable	Unfavourable
Without Nitrification	100 - 150	120 - 180
Nitrification (and Denitrification)	100 - 150	120 - 180
Sludge Stabilization	75 - 120	100 - 150

The respectively lower values for the sludge volume index (SVI) can be applied, if:

- primary settling is dispensed with,
- a selector or an anaerobic mixing tank is placed upstream,

- the biological reactor is designed as a cascade (plug flow)

The concentration of mixed liquor suspended solids (SS_{AT}) is determined in the process of dimensioning the secondary settling tank.

Volume of the Biological Reactor (ATV A131E/chapter 5.2.6)

The required mass of the suspended solids in the biological reactor is:

$M_{SS,AT} = t_{SS,Dim} * SP_d$ (kg) (4-12)

The volume of the biological reactor is obtained from the following formula:

$V_{AT} = M_{SS,AT}/SS_{AT}$ (4-13)

Required Recirculation and Cycle Time (ATV A131E/chapter 5.2.7)

The necessary total recirculation flow ratio (RC) for pre-anoxic zone denitrification results using $S_{NH4,N}$, the ammonium nitrogen concentration to be nitrified, as follows:

$RC = (S_{NH4,N}/S_{NO3,N}) - 1$ (4-14)

With an intermittent denitrification process the cycle duration ($t_T = t_N + t_D$) can be estimated from the following formula:

$t_T = t_R * (S_{NO3,EST}/S_{NH4,N})$ (h,d) (4-15)

Where;

t_T : Cycle time with intermittent process

t_N : Duration of the nitrification phase with intermittent process

t_D : Duration of denitrification phase with intermittent process

t_R : Retention period (e.g. $t_R = V_{AT} : Q_{h,DW}$)

The retention time $t_R = V_{AT}/Q_{h,DW}$ and the cycle time (t_T) have the same unit. A cycle time of less than 2 hours is not recommended.

Oxygen Transfer (ATV A131E/chapter 5.2.8)

The oxygen uptake is made up the consumption for carbon removal (including the endogenous respiration) and, if necessary, the requirement for nitrification as well as the saving of oxygen from denitrification. For carbon removal the following approach, using Hartwig coefficients, oxygen transfer for carbon removal is:

$$O_{Ud,C} = B_{d,BOD} * \{0.56 + [(0.15*t_S*F_T)/(1+0.17*t_{SS}*F_T)]\} \text{ (kg } O_2\text{/d)} \qquad (4\text{-}16)$$

For nitrification the oxygen consumption is assumed to be 4.3 kg O_2 per kg oxidized nitrogen taking into account the metabolism of the nitrificants. With denitrification one reckons for carbon removal with 2.9 kg O_2 per kg denitrified nitrate nitrogen.

Oxygen transfer for nitrification is obtained from the following formula:

$$O_{Ud,N} = Q_d*4.3*(S_{NO3,D} - S_{NO3,IAT} + S_{NO3,EST})/1000 \text{ (kg } O_2\text{/d)} \qquad (4\text{-}17)$$

Oxygen transfer for denitrification is obtained from the following formula:

$$O_{Ud,D} = Q_d*2.9*S_{NO3,D}/1000 \text{ (kg } O_2\text{/d)} \qquad (4\text{-}18)$$

The oxygen uptake rate for daily peak is obtained from the following formula:

$$OU_h = [f_C*(OUd_{,C} - OU_{d,D}) +f_N*OU_{d,N}]/24 \text{ (kg}O_2\text{/h)} \qquad (4\text{-}19)$$

The peak factor f_C represents the ratio of the oxygen uptake rate for carbon removal in the peak hour to the average daily oxygen uptake rate. The peak factor f_N is equivalent to the ratio of the TKN load in the 2h peak to the 24h average load. With normal inflow conditions $f_{C \text{ and}}$ f_N can be taken from Table 4.15.

Table 4.15 Peak factors for the oxygen uptake rate (to cover the 2h peaks compared with the 24h average (ATV A131E, 2000)

	Sludge age (days)					
	4	6	18	10	15	26
f_C	1.3	1.25	1.2	1.2	1.15	1.1
f_N for $B_{d,BOD,I} \leq 1200$ kg/d	-	-	-	2.5	2.0	1.5

f_N for $B_{d,BOD,I} > 6000$ kg/d			2.0	1.8	1.5	-

Suspended Solids Concentration in the Return Sludge (ATV A131E/chapter 6.3)

The achievable suspended solids concentration in the bottom sludge SS_{BS} (average suspended solids concentration in the sludge removal flow) can be estimated empirically from the following formula in dependence on the sludge volume index SVI and the thickening time t_{Th}.

$SS_{BS} = 1000/SVI * (t_{TH})^{2/3}$ (kg/m^3) (4-20)

The suspended solids concentration of the return sludge (SS_{BR}), as a result of the dilution with the short-circuit sludge flow, can be assumed in simplified from to be:

with scraper facilities $SS_{RS} \sim 0.7*SS_{BS}$

with suction facilities $SS_{RS} \sim 0.5$ to $0.7*SS_{BS}$

The value of the 0.7 is defined as dilution factor of the return sludge.

Surface Overflow Rate and Sludge Volume Surface Loading Rate (ATV A131E/chapter 6.5)

The surface overflow rate q_A is calculated from the permitted sludge volume loading rate q_{SV} and the diluted sludge volume DSV as:

$q_A = q_{SV}/DSV = q_{SV}/(SS_{ET}*SVI)$ (m/h) (4-21)

The Key Information

In this study the minimum design SRT (sludge retention time) was considered as 15 days. In fact, the sludge age varies depending on the process as given below:

- For carbon removal : 5 days
- For nitrification : 8 - 10 days
- For denitrification : 10 - 20 days
- For aerobic stabilization of sludge : 25 - 30 days

Note: To avoid blocking the pores of the membrane, the sludge production ratio (SS/BOD) should be between 0.4 - 1.2.

Waste activated sludge (WAS) production is calculated according to ATV A131E (chapter 5.2.4) and this value changes depending on the SRT and wastewater composition. It is possible to calculate the volume of the bioreactor from the following formula:

- ✓ WAS Ratio = 0.5-1.3 kg MLSS/kg BOD + Sludge Chem. Phosp. Removal
- ✓ Volume of the bioreactor (V, m^3) = (SRT * WAS) / $MLSS_{BR}$

and waste active sludge production (SP_d) can be calculated from the following formula:

- ✓ WAS Production (SP_d) = WAS Ratio * C_{BOD5}

For municipal wastewater at moderate temperatures, effective biological treatment can be achieved at F/M ratios below 0.08 kg-BOD/kg MLSS.day, under average daily load conditions. For basic treatment, the system should be designed to ensure full nitrification. A minimum SRT of 15 days is recommended to achieve this aim. If the F/M ratio is higher than 0.8 kg BOD/kg MLSS.day, the SRT value should be increased and F/M ratio can be calculated from the following formula:

- ✓ F/M Ratio = C_{BOD5}/Biomass
- ✓ Biomass = WAS Production (SP_d) * Design SRT

According to the above formula, the volume of the bioreactor can be calculated from the following formula:

- ✓ V_{BR} = Biomass/$MLSS_{BR}$

HRT varies according to the characteristics of the wastewater. The volume of the treatment tank should not be determined by HRT only. The recommended minimum HRT is 6 hour. In the case of typical municipal sewage treatment with MLSS concentration & operating at mild temperatures, approximately 6 to 8 hours of HRT under average flow conditions may be appropriate in order to avoid ammonia peaks during hydraulic peak flows. HRT and the volume bioreactor depended on the HRT are calculated from the following formula:

- ✓ HRT = $V_{BR}/Q_{average}$
- ✓ $V_{BRHRT} = HRT_{min} * Q_{average}$

As the above results, the larger volume is determined for the needed biological volume. This result is used for the calculation of an activated sludge bioreactor system. However, in order to a biological volume in MBR tank, it must be taken into account the needed bioreactor volume can be calculated from the following formula:

- ✓ Biological Volume in MBR Tank = V_{MBR} - (Biological Vol. in MBR * No. of Mod.)
- ✓ Needed Volume Bioreactor (V_{BR}) = V_{BR} - V_{MBR}

Typical parameters used in the design of biological processes are shown in Table 4.16.

Table 4.16 The typical biological parameters

Parameter	Unit	Design Range	Typical Value
BOD Loading Rate	kgBOD/m^3.d	0.5 - 2	1
F/M Ratio	kgBOD/kgSS.d	< 0.08	0.06
SRT	days	8 - 30	15
HRT	h	6 - 10	>6
MLSS	g/L	8 - 12	10
Sludge Recycle Rate	%	200 - 600%	200%
Oxygen Transfer Efficiency	%	50 - 60%	60%
Sludge Production	kgSS/kgBOD.d	0.6 - 1.2	1.0
Anoxic Volume	% of biological volume	15 - 50	40

CHAPTER FIVE

RESULTS AND DISCUSSION

Using the MBR design methods that were explained in the previous chapter, it was tried to determine the effects of some significant parameters on the MBR systems operation. The required biological reactor volumes and oxygen demands were determined according to various MLSS, SRT, and recycle ratio values. Results are discussed for integrated and separated system configurations, separately (Figure 5.1 and Figure 5.2).

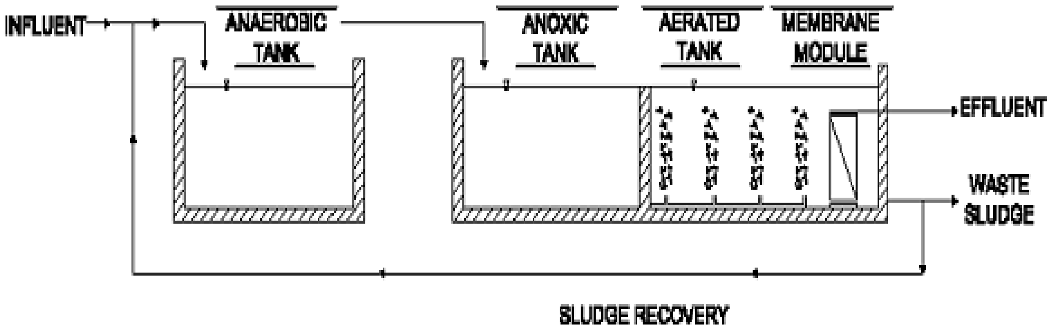


Figure 5.1 The process flow diagram for integrated system

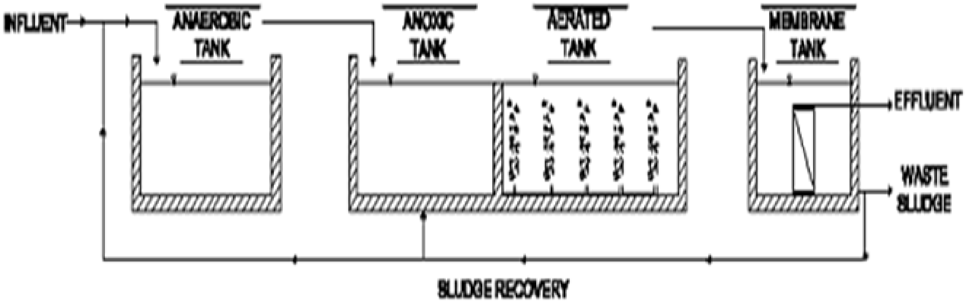


Figure 5.2 The process flow diagram for separated system

5.1 The Results Obtained for the Integrated System

5.1.1 Effects of SRT Changes

Determining the optimum SRT is very significant for biological systems since it effects the system performance, capital and operating costs, and etc. To determine the effect of sludge retention time changes on the volume of the reactors and oxygen demand, various SRT values changing between 15 to 50 days were examined. MLSS and recycle ratio kept constant at 15 gr/L and 200%, respectively (Table 5.1).

Table 5.1 The effects of SRT changes

SRT (day)	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
MLSS (g/L)	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**
Recycle (%)	**200**	**200**	**200**	**200**	**200**	**200**	**200**	**200**
Sludge Production (kgSS/kgBOD.d)	1	1	1	1	1	1	1	1
WAS Ratio (kgMLSS/kgBOD)	0.974	0.919	0.919	0.891	0.891	0.863	0.863	0.863
WAS Production (kgMLSS/d)	351	331	331	321	321	311	311	311
F/M Ratio (kgBOD/kgMLSS.d)	0.07	0.05	0.04	0.04	0.03	0.03	0.03	0.02
Biomass (kg)	5,262	6,616	8,27	9,624	11,228	12,432	13,986	15,540
HRT (h)	7.02	8.82	11.03	12.83	14.97	16.58	18.65	20.72
BOD Volumetric Load (kgBOD/m3.d)	1.03	0.82	0.65	0.56	0.48	0.43	0.39	0.35
Volume Bio-P (m3)	75	75	75	75	75	75	75	75
Volume DENI (m3)	116	146	182	212	248	274	308	342
Volume NITRI (m3)	97	157	231	291	363	417	486	556
Total Volume (m3)	288	378	488	578	686	766	869	973
Oxygen Demand (kgO2/kg BOD)	1.32	1.37	1.40	1.43	1.45	1.46	1.47	1.48

Longer HRT and lower F/M ratio values were calculated for longer SRT. The recycle ratio has no effect on the volume of the bioreactor for the integrated systems. The total bioreactor volume sharply increases with increasing SRT. Similar tendencies were obtained for anoxic and aerobic regions. However, required Bio-P tank volume remains constant (Figure 5.3). So, it can be concluded that SRT significantly effects the nitrification and denitrification phenomena. As can be seen from the Figure 5.4, oxygen demand slightly increased with SRT. It increased from 1.32 to 1.48 kg O_2/kg BOD for SRT of 15 to 50 days (Figure 5.4).

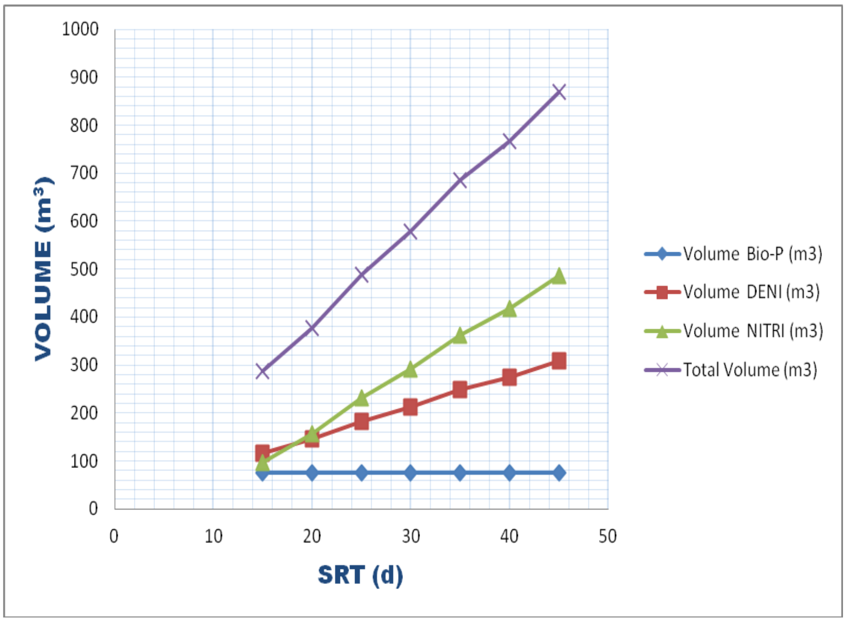


Figure 5.3 The relationship between SRT and volume of bioreactors for the integrated system

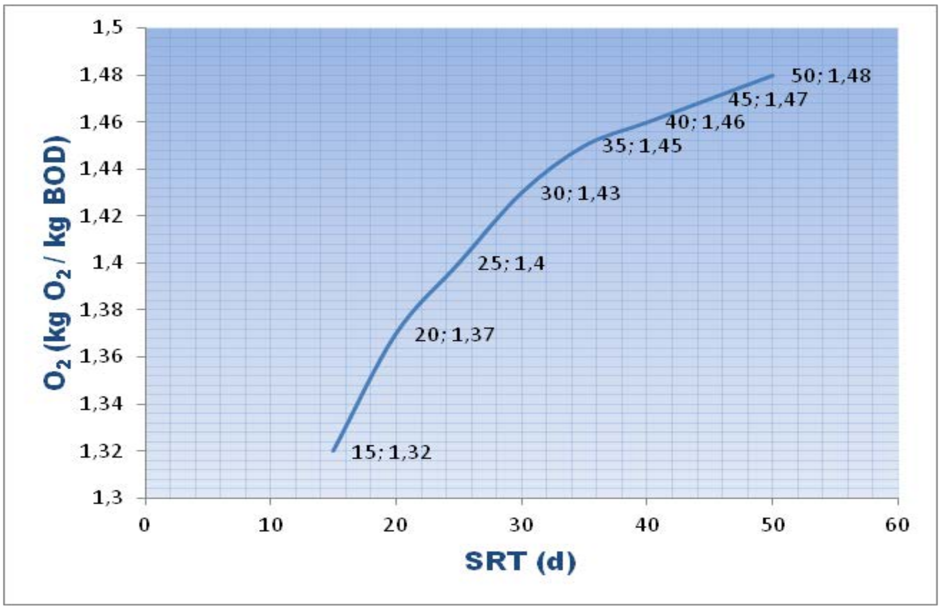


Figure 5.4 The relationship between SRT and oxygen demand for the integrated system

5.1.2 Effects of Recycle Ratio

In order to determine the recycle ratio effects, various recycle ratios changing between 50% - 200 % were examined. In this case, SRT and MLSS kept constant at 20 days and 15 g/L, respectively. The results are given in Table 5.2.

Table 5.2 The effects of recycle ratio changes

Recycle (%)	**50**	**100**	**150**	**200**
SRT (day)	**20**	**20**	**20**	**20**
MLSS (g/L)	**15**	**15**	**15**	**15**
Sludge Production (kgSS/kgBOD.d)	1	1	1	1
WAS Ratio (kgMLSS/kgBOD)	0.919	0.919	0.919	0.919
WAS Production (kgMLSS/d)	331	331	331	331
F/M Ratio (kgBOD/kgMLSS.d)	0.05	0.05	0.05	0.05
Biomass (kg)	6,616	6,616	6,616	6,616
HRT (h)	8.82	8.82	8.82	8.82
BOD Vol. Load (kgBOD/m3.d)	0.82	0.82	0.82	0.82
Volume Bio-P (m3)	37.5	50	62.5	75
Volume DENI (m3)	146	146	146	146
Volume NITRI (m3)	157	157	157	157
Total Volume (m3)	341	353	366	378
Oxygen Demand (kgO2/kg BOD)	1.37	1.37	1.37	1.37

As can be seen from Figure 5.5, the recycle ratio only effects the volume of the Bio-P tank. Because of it is an integrated system, there is no effect on the volume of the anoxic and aerobic tank. In integrated system, the membrane module is placed directly into the bioreactor wherein any sludge recycle is not necessary. The sludge recirculation is only carried out from the aerobic tank to anaerobic tank (Bio-P tank). Besides, since there is not an internal recycle, the recycle ratio has no effect on the oxygen demand.

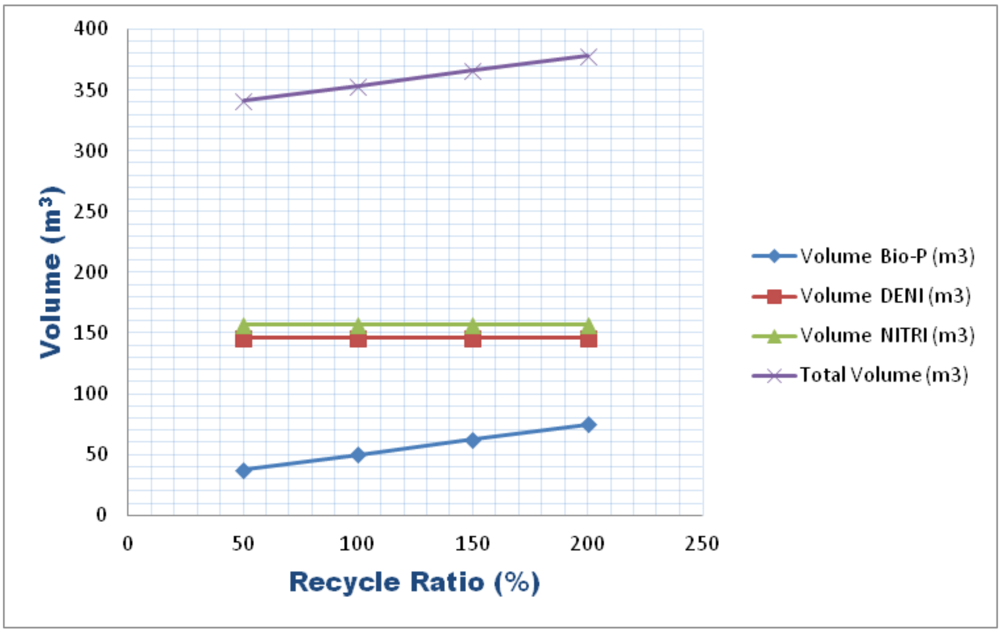


Figure 5.5 The relationship between recycle ratio and volume of bioreactors for the integrated system

5.1.3 Effects of MLSS Changes

MLSS concentrations changing in the range of 7 – 20 g/L were investigated to determine the effects of MLSS concentrations on the volume of the bioreactor and on the needed oxygen demand for the integrated system. At this time, SRT value was kept constant at 20 d and the recycle ratio was kept at 200 % (Table 5.3).

Table 5.3 The effect of MLSS changes

MLSS (g/L)	**7**	**10**	**12**	**15**	**18**	**20**
SRT (day)	**20**	**20**	**20**	**20**	**20**	**20**
Recycle (%)	**200**	**200**	**200**	**200**	**200**	**200**
Sludge Production (kgSS/kgBOD.d)	1	1	1	1	1	1
WAS Ratio (kgMLSS/kgBOD)	0.919	0.919	0.919	0.919	0.919	0.919
WAS Production (kgMLSS/d)	331	331	331	331	331	331
F/M Ratio (kgBOD/kgMLSS.d)	0.05	0.05	0.05	0.05	0.05	0.05
Biomass (kg)	6,616	6,616	6,616	6,616	6,616	6,616
HRT (h)	18.90	13.23	11.03	8.82	7.35	6.62
BOD Vol. Load (kgBOD/m3.d)	0.38	0.54	0.65	0.82	0.98	1.09
Volume Bio-P (m3)	75	75	75	75	75	75
Volume DENI (m3)	312	219	182	146	122	110
Volume NITRI (m3)	495	305	231	157	108	83
Total Volume (m3)	882	599	488	378	305	268
Oxygen Demand (kgO2/kg BOD)	1.37	1.37	1.37	1.37	1.37	1.37

As it is expected, the total bioreactor volume decreases sharply with MLSS. While the anoxic and aerobic tanks volume decreases with MLSS, the volume of the Bio-P tank remains constant (Figure 5.6). MLSS concentration changes have no effect on the oxygen demand.

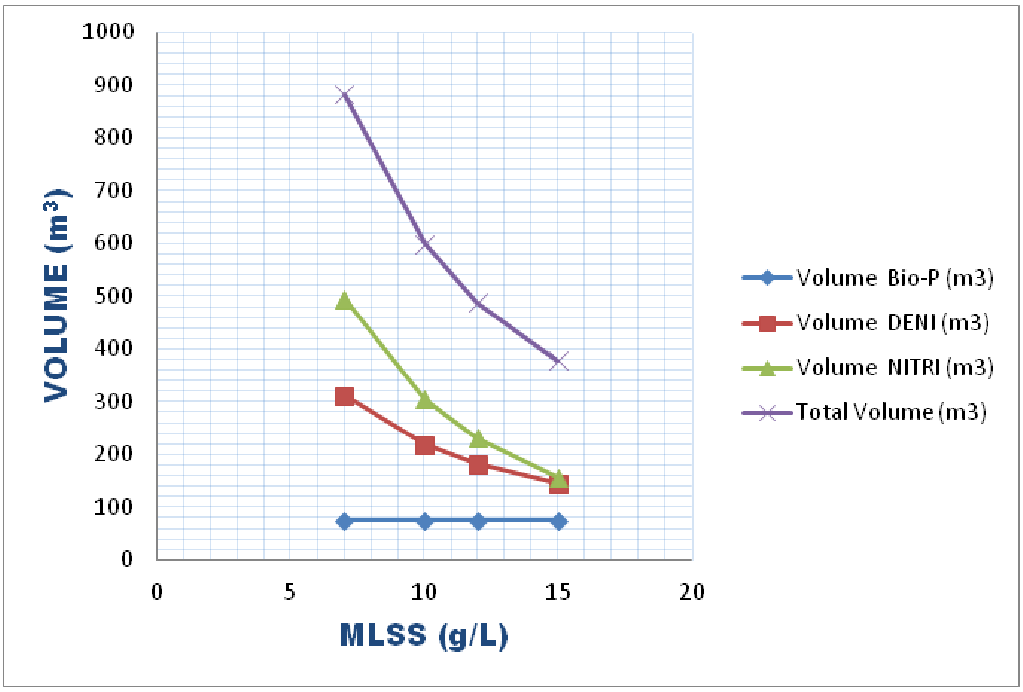


Figure 5.6 The relationship between MLSS and volume of bioreactor for the integrated system

5.2 The Results Obtained for the Separated System

5.2.1 Effects of SRT

As in integrated system, the impact of the sludge retention time on the volume of the bioreactor and oxygen demand was investigated. For this purpose, MLSS value was kept constant at 15 g/L and likewise, the recycle ratio was kept at 200 %. Results are given in Table 5.4. Similar results were obtained for both integrated (internal) and separated (external) systems.

Table 5.4 The effects of SRT changes

SRT (day)	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
MLSS in the MBR Tank (g/L)	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**
MLSS in the Bioreactor (g/L)	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**
Recycle (%)	**200**	**200**	**200**	**200**	**200**	**200**	**200**	**200**
Sludge Production (kgSS/kgBOD.d)	1	1	1	1	1	1	1	1
WAS Ratio (kgMLSS/kgBOD)	0.974	0.919	0.919	0.891	0.891	0.863	0.863	0.863
WAS Production (kgMLSS/d)	351	331	331	321	321	311	311	311
F/M Ratio (kgBOD/kgMLSS.d)	0.07	0.05	0.04	0.04	0.03	0.03	0.03	0.02
Biomass (kg)	5,262	6,616	8,27	9,624	11,228	12,432	13,986	15,540
HRT (h)	10.52	13.23	16.54	19.25	22.46	24.86	27.97	31.08
BOD Vol. Load (kgBOD/m3.d)	0.68	0.54	0.44	0.37	0.32	0.29	0.26	0.23
Volume Bio-P (m3)	75	75	75	75	75	75	75	75
Volume DENI (m3)	174	219	273	318	371	411	462	513
Volume NITRI (m3)	214	305	416	506	614	694	799	903
Total Volume (m3)	463	599	764	899	1060	1180	1336	1491
Oxygen Demand (kgO2/kg BOD)	1.32	1.37	1.40	1.43	1.45	1.46	1.47	1.48

The volume of the bioreactor and the oxygen demand was calculated depending on the different SRT values for the separated system. The volume of the anoxic and aerobic tanks increases with increasing SRT while the volume of the Bio-P tank remains constant (Figure 5.7). As can be seen from the Figure 5.8, as in the integrated system, SRT has an influence on the oxygen demand.

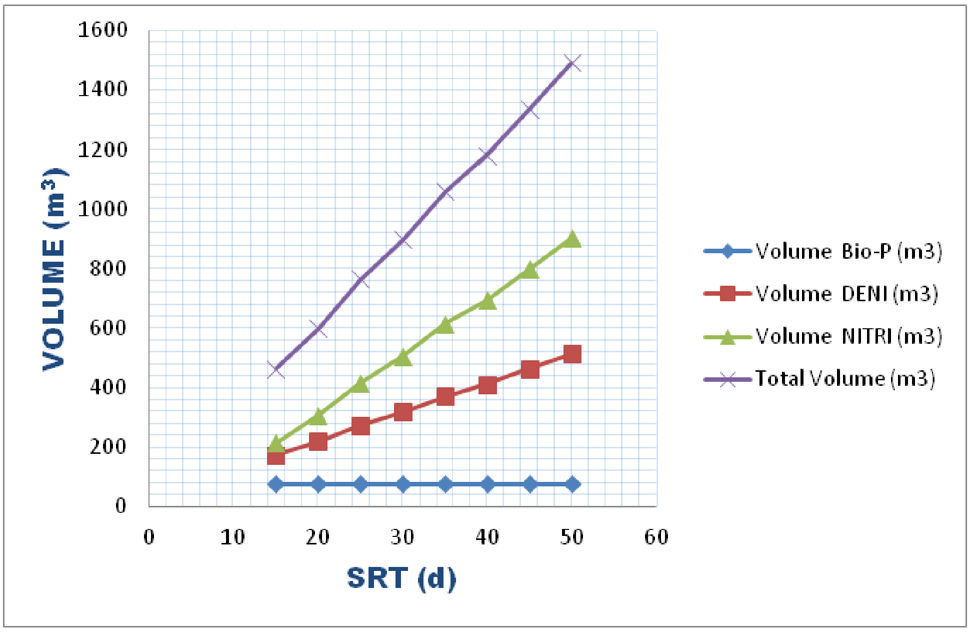


Figure 5.7 The relationship between SRT and volume of bioreactor for the separated system

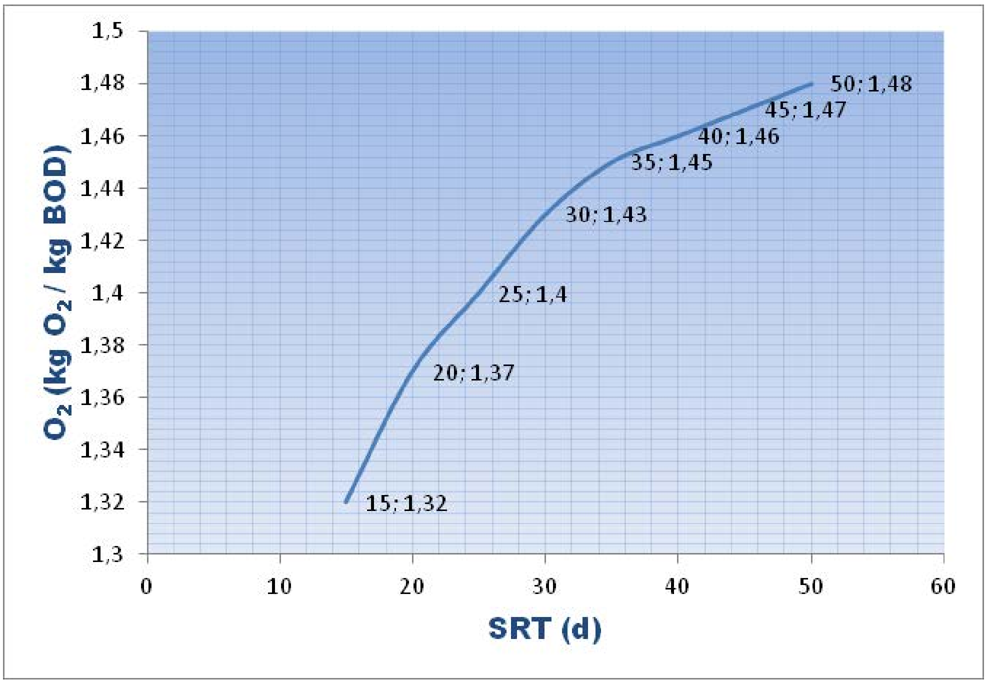


Figure 5.8 The relationship between SRT and oxygen demand for the separated system

5.2.2 Effects of Recycle Ratio

Similar assumptions were made also for separated system. Recycle ratios changing between 50% - 200 % were examined at constant SRT and MLSS of 20 days and 15 g/L, respectively. The results are given in Table 5.5.

Table 5.5 The effects of recycle ratio changes

Recycle (%)	**50**	**100**	**150**	**200**
SRT (day)	**20**	**20**	**20**	**20**
MLSS in the Bioreactor (g/L)	**5**	**7.5**	**9**	**10**
MLSS in the MBR Tank (g/L)	**15**	**15**	**15**	**15**
Sludge Production (kgSS/kgBOD.d)	1	1	1	1
WAS Ratio (kgMLSS/kgBOD)	0.919	0.919	0.919	0.919
WAS Production (kgMLSS/d)	331	331	331	331
F/M Ratio (kgBOD/kgMLSS.d)	0.05	0.05	0.05	0.05
Biomass (kg)	6,616	6,616	6,616	6,616
HRT (h)	8.82	8.82	8.82	8.82
BOD Vol. Load (kgBOD/m3.d)	0.27	0.41	0.49	0.54
Volume Bio-P (m3)	37.5	50	62.5	75
Volume DENI (m3)	437	292	243	219
Volume NITRI (m3)	748	453	354	305
Total Volume (m3)	1223	795	660	599
Oxygen Demand (kgO2/kg BOD)	1.37	1.37	1.37	1.37

In this case, all reactor volumes were effected from recycle ratio changes. Unlike integrated system, as can be seen from the Figure 5.9 the recycle ratio has more effect on the volume of the bioreactor. However, while the anoxic and aerobic tanks volume decreases, the volume of the Bio-P tank increases with the increasing recycle ratio. Similar to the integrated system the oxygen demand is not affected from recycle ratio and changing of the recycle ratio also effect the MLSS value in the bioreactor tank because of it is a separated system (Figure 5.10).

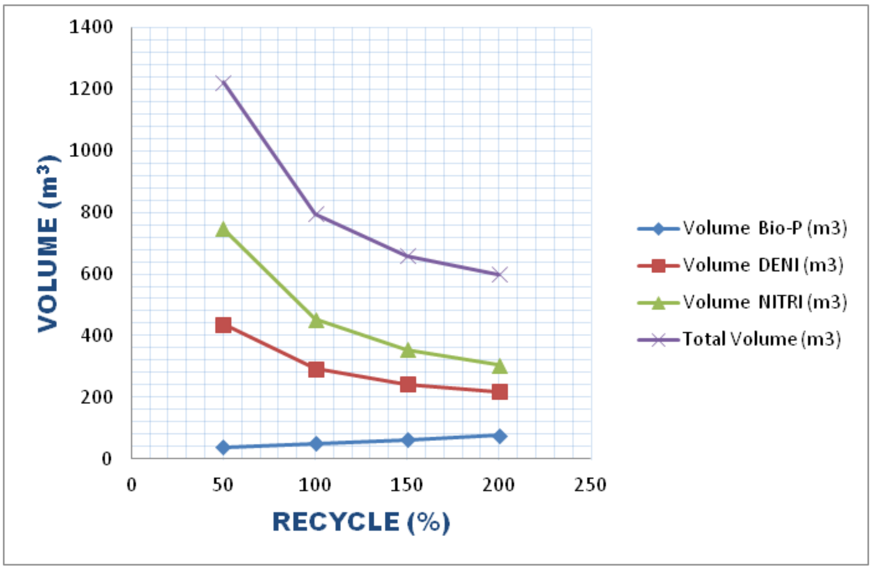


Figure 5.9 The relationship between recycle ratio and volume of bioreactor for the separated system

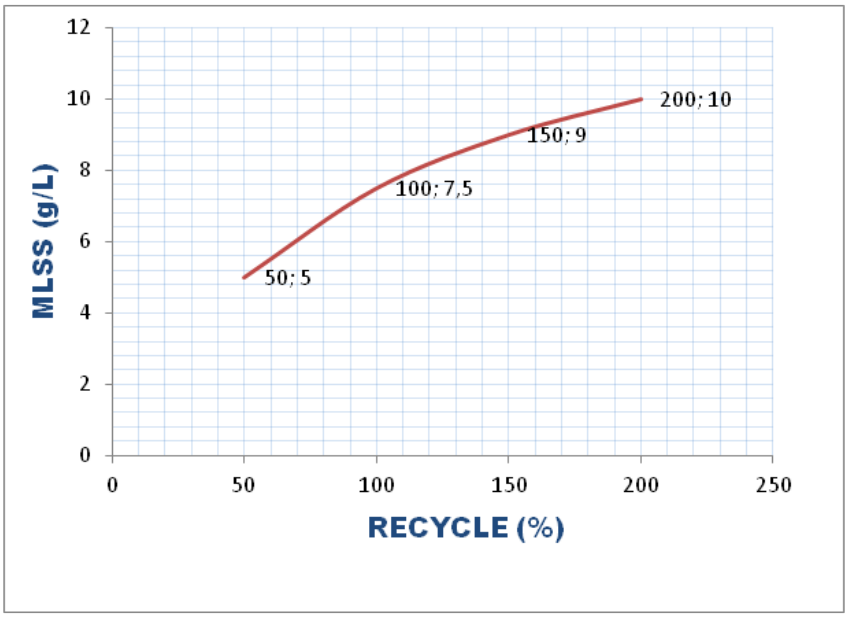


Figure 5.10 The relationship between recycle ratio and MLSS for the separated system

5.2.3 Effects of MLSS

The volume of the bioreactor and the oxygen demand was calculated for various MLSS concentration at constant SRT and recycle ratio of 20 d and 200 %, respectively (Table 5.6).

Table 5.6 The effects of MLSS changes

MLSS in the MBR Tank (g/L)	**7**	**10**	**12**	**15**	**18**	**20**
MLSS in the Bioreactor (g/L)	**4.66**	**6.66**	**8**	**10**	**12**	**13.33**
SRT (day)	**20**	**20**	**20**	**20**	**20**	**20**
Recycle (%)	**200**	**200**	**200**	**200**	**200**	**200**
Sludge Production (kgSS/kgBOD.d)	1	1	1	1	1	1
WAS Ratio (kgMLSS/kgBOD)	0.919	0.919	0.919	0.919	0.919	0.919
WAS Production (kgMLSS/d)	331	331	331	331	331	331
F/M Ratio (kgBOD/kgMLSS.d)	0.05	0.05	0.05	0.05	0.05	0.05
Biomass (kg)	6,616	6,616	6,616	6,616	6,616	6,616
HRT (h)	28.35	19.85	16.54	13.23	11.03	9.92
BOD Vol. Load (kgBOD/m3.d)	0.25	0.36	0.44	0.54	0.65	0.73
Volume Bio-P (m3)	75	75	75	75	75	75
Volume DENI (m3)	468	328	273	219	182	164
Volume NITRI (m3)	811	526	416	305	231	194
Total Volume (m3)	1354	929	764	599	488	433
Oxygen Demand (kgO2/kg BOD)	1.37	1.37	1.37	1.37	1.37	1.37

As can be seen from the Figure 5.11, the total bioreactor volume decreases with MLSS. The volume of the anoxic and aerobic tanks decreased with MLSS; however, the volume of the Bio-P tank remains constant. MLSS has no effect on the oxygen demand. MLSS value in the bioreactor tank also increased with MLSS in the MBR tank (Figure 5.12).

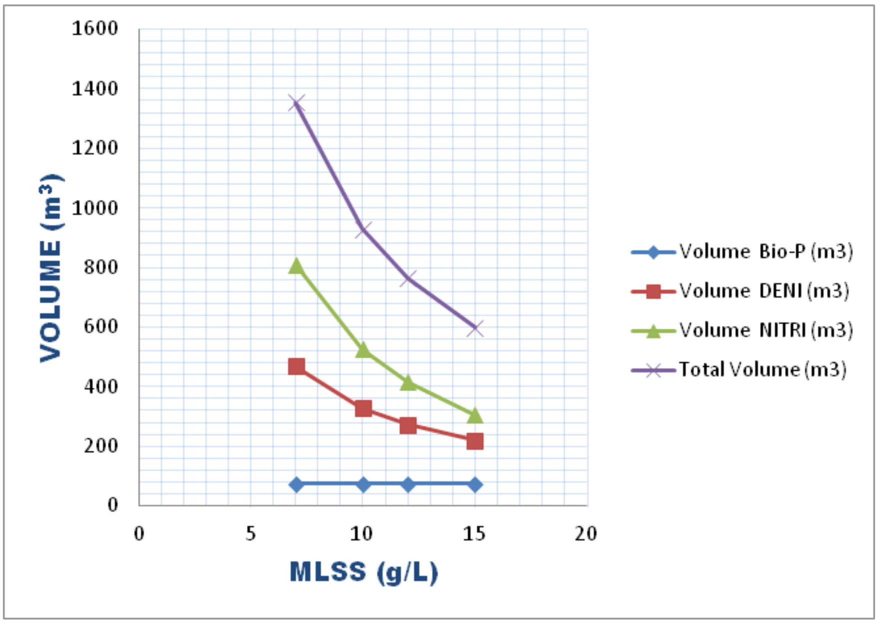


Figure 5.11 The relationship between MLSS and volume of bioreactor for the separated system

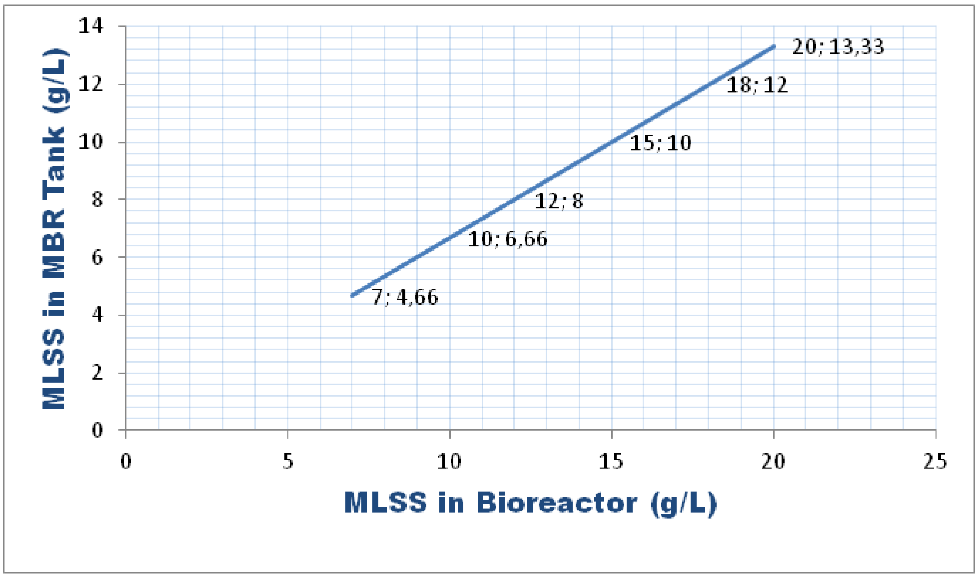


Figure 5.12 The relationship between MLSS in MBR tank and MLSS in bioreactor for the separated system

5.3 Comparison of the Results

In the scope of this thesis, the effect of some operating parameters including SRT, recycle ratio, and MLSS, on the volume of the total bioreactor and oxygen demand in bioreactors for integrated and separated MBR systems is evaluated by using ATV A131E. Comparison of the results is summarized in Table 5.7.

Table 5.7 The effects of the some parameters for the integrated and separated system

Parameter	Integrated MBR System		Separated MBR System	
	Volume of the total reactor	Oxygen demand	Volume of the total reactor	Oxygen demand
SRT	√ (increase)	√ (increase)	√ (increase)	√ (increase)
Recycle Ratio	√ (increase)	X	√ (decrease)	X
MLSS	√ (decrease)	X	√ (decrease)	X

"√" indicates that this parameter has influence potential

"X" indicates that this parameter has not influence potential

As seen from the table, SRT is found as the most significant parameter among the evaluated operating parameters for both integrated and separated MBR systems. At all situations, volume of the total reactor increased with increasing SRT values. However, higher reactor volumes are needed for separated systems compared to integrated systems. On the other hands, volume increasing rate versus SRT is almost same, approximately 3.3 times higher total bioreactor volume is needed while the SRT increased from 15 to 50 days for both configurations.

There are many studies about the effects of the SRT values on the membrane bioreactor (Trussel et al., 2008; Pollice et al., 2007). Especially the value of SRT has significantly important for biological reactor parts of MBR systems. Because, the SRT value affects the mixed liquor characteristics and longer SRT could cause lower F/M ratio.

At both configuration options, volume of the Bio-P tank kept constant while the volume of the nitrification tank increases rapidly with increasing SRT value. As the membrane kept nitrifying microorganism in the reactors at complete sludge retention, these autotrophic nitrifiers could profiliferate without any loss (Ke & Junkin, 2009). Consequently, a higher nitrification rate could be achieved in MBR system than in the conventional biological treatment plants (Chang, et al., 2002). The high sludge concentration with high SRT is convenient to the growth of nitrifiers, which resulted in an increase in NH_4^+-N removal rate (Ke & Junkin, 2009).

MBR technology was found a chance to practice into larger plants after the mid 90s and the recent trend is to apply SRT around 10-20 days, resulting in more manageable MLSS levels around 10-15 g/L. According to the studies (Coppen, 2004; AMTA, 2007) the MLSS in the MBR tank should be between 7 - 18 g/L during the operation. Generally, the recommended value for MLSS is 15 g/L. The main reason of this is the longer SRT value increases the oxygen demand, bioreactor volume and thereby increases investment and operational costs. But, compared with the longer SRT value, membrane fouling has seen more often than lower SRT value (Trussel, et al., 2008).

The hydraulic retention time (HRT) and the volume of the total bioreactor decreased with increasing MLSS concentration. When MLSS increased from 7 to 20 g/L, about 3.2 times lower bioreactor volume is needed for both integrated and separated MBR configurations. MLSS parameter has no effect on oxygen demand. It kept constant as 1.37 kg O_2/kg BOD at all MLSS applications.

Recycle ratio has different effects for integrated and separated MBR systems. For integrated systems, it only effects the Bio-P tank volume. When recycle ratio increased 4 times, the volume of the Bio-P tank increased 2 times and because of this increase total bioreactor volume is also increased. However, for separated systems, total bioreactor volume decreased since denitrification and nitrification tank volumes decreased with increasing recycle ratio. In this case, the volume of the Bio-P tank again increased 2 times.

CHAPTER SIX
CONCLUSIONS

6.1 Conclusions

Membrane bioreactor system performance depends on the both bioreactor and membrane parts of the system. In this thesis, determination of the effect of SRT, recycle ratio, and MLSS parameters on the volume of the total bioreactor and oxygen demand in bioreactors for integrated and separated MBR systems was aimed. For this purpose, ATV A131E design approach was used and evaluations were made for both integrated and separated systems. In accordance with this study, the following conclusions were obtained:

- SRT is found as the most significant parameter among the evaluated operating parameters for both integrated and separated MBR systems. At all situations, volume of the total reactor increased with increasing SRT values.
- Approximately 3.3 times higher total bioreactor volume is needed while the SRT increased from 15 to 50 days for both configurations.
- 3.2 times lower bioreactor volume is needed for both integrated and separated MBR configurations when MLSS increased from 7 to 20 g/L.
- MLSS parameter has no effect on oxygen demand.
- For integrated systems, recycle ratio changes only effects the Bio-P tank volume.
- For separated systems, recycle ratio directly effects the denitrification and nitrification tank volumes. They decreased with increasing recycle ratio.

6.2 Recommendations

Energy consumption and operating costs are one of the most important items for wastewater engineering. MBR systems have several advantages comparing to conventional activated sludge systems but a higher energy requirement is the severe problem for MBR systems operating. Operating cost can be reduced by optimization of energy consumption. It can also be possible to decrease carbon footprint by decreasing energy consumption. For this reason, detailed studies should be carried out on the designing and operating of MBR systems.

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