Holistic Evaluation of Cruise Vessel Advanced Wastewater Purification Process through Mass Balance

Jussi Vikainen

Bachelor’s thesis
December 2012
Degree Programme in
Environmental Engineering

TAMPEREEN AMMATTIKORKEAKOULU
Tampere University of Applied Sciences

ABSTRACT

Tampereen ammattikorkeakoulu
Tampere University of Applied Sciences
Degree Programme in Environmental Engineering

VIKAINEN, JUSSI:

Holistic Evaluation of Cruise Vessel Advanced Wastewater Purification Process through Mass Balance

Bachelor's thesis 39 pages, appendices 2 pages
December 2012

This thesis was made for Royal Caribbean Cruises Ltd. Technical New Building Office in Turku to find out the amounts and concentrations of different wastewater streams generated on board cruise ships as accurately as possible and to develop a simple "mass balance" tool for evaluating hydraulic, biological and nutrient loading on the wastewater treatment system. The work included analysing and compiling the measurement data as well as developing the calculation tool with Microsoft Excel. The written report was to include a literary introduction to wastewater treatment technologies used on ships as well as relevant legislation.

Mass balance charts are made in the ship's design stage by the equipment manufacturers to determine the expected wastewater loading. The need for a simple mass balance model comes from the fact that often these estimations vary considerably between manufacturers.

The measured values were divided by the total amount of passengers and crew on board the ship from where the measurements were taken to reach comparable per person values. The mass balance tool is based on the assumption that wastewater amounts increase linearly with the passenger capacity of the ship. This relationship gives the tool adequate accuracy to predict wastewater amounts for different sized ships. Some problems were encountered with inconsistencies in the background data as it was collected from several different sources. The background data for the mass balance model is not published in this thesis. Furthermore some references are made to unpublished documents such as technical specifications with permission from the manufacturer.

Key words: wastewater treatment, cruise ships, mass balance

TIIVISTELMÄ

Tampereen ammattikorkeakoulu
Tampere University of Applied Sciences
Degree Programme in Environmental Engineering

VIKAINEN, JUSSI:
Risteilylaivojen jätevesimäärien arviointi massataseen avulla

Opinnäytetyö 39 sivua, joista liitteitä 2 sivua
Joulukuu 2012

Tämän opinnäytetyön toimeksiantajana oli Royal Caribbean Cruises Ltd.:n tekninen toimisto Turussa. Opinnäytetyön tarkoitus oli selvittää risteilylaivoilla syntyvien jätevesien hydraulinen sekä biologinen kuormitus sekä luoda massatase–malli, jonka avulla erikokoisten laivojen jätevesimääriä voisi helposti laskea matkustajamäärän mukaan. Lisäksi malliin on laskettu tiettyjä jäteveden puhdistukselle keskeisiä parametrejä kuten biologisen prosessin ylläpitämiseen tarvittava ilmamäärä. Työ sisälsi mittaustulosten keräyksen ja analysoinnin sekä massatase-mallin tekemisen Microsoft Excel –ohjelmalla.

Laivan suunnitteluvaiheessa jätevedenpuhdistuslaitosten toimittajat tekevät massatase-kaavioita arvioimaan veden virtausmäärää, orgaanisen aineksen, ravinteiden sekä kiintoaineksen pitoisuuksia. Usein kuitenkin arviot vaihtelevat huomattavasti. Opinnäytetyön massatase-mallin laskurin tavoitteena on antaa mahdollsimman tarkkaa, mitattuihin arvoihin pohjautuvaa dataa suunnittelun avuksi.

Mittaustulokset jaettiin laivan matkustajien ja henkilökunnan kokonaismäärällä, näillä per henkilö arvoilla malli laskee jäteveden sekä orgaanisen aineen ja ravinteiden kuormituksen annetulle henkilömäärälle. Opinnäytetyön massatase-malli perustuu mahdollisimman paljon olemassa olevien laivojen mitattuihin jäteveden virtausmääriin ja pitoisuuksiin. Siitäkin huolimatta joitain tietoja jouduttiin arvioimaan kirjallisuuden pohjalta taustatiedon ollessa riittämätön tai ristiriitainen. Koska mittaustuloksia kerättiin useasta eri lähteestä, on jälkikäteen hyvin vaikeaa ottaa kantaa poikkeaviin arvoihin ja tulosten tarkkuuteen. Pääsääntönä poikkeavia arvoja ei poistettu, varsinkin koska mittaukset oli suorittanut jokin muu taho. Mittaustulokset ja tekniset erittelyt, joihin raportissa, viitataan ovat luottamuksellisia.

Asiasanat: jäteveden puhdistus, risteilylaivat, massatase

CONTENTS

ABBREVIATIONS AND TERMS

AWP	Advanced Wastewater Purification, common term used to describe any wastewater treatment system on board a ship
Bio residue	In this thesis bio residue refers to the solids removed only from the biological process of the system, this waste does not contain any plastics.
Bio sludge	In this thesis bio sludge refers to the solids that contain also plastics removed at the primary screens. These two terms are commonly used in ship building to distinguish between the two types of solids, since the bio residue can be pumped overboard, whereas bio sludge, containing plastics cannot be.
BOD	Biochemical Oxygen Demand, a water quality measure expressed in mg/l
COD	Chemical Oxygen Demand, a water quality measure expressed in mg/l
HRT	Hydraulic Retention Time, the time it takes for the waste water to flow through the treatment system, measured in hours
MLSS	Mixed Liquor Suspended Solids, the total amount of solids in the aerobic process, containing both organic and inorganic constituents, expressed in mg/l
MLVSS	Mixed Liquor Volatile Suspended Solids, the portion of solids in the aerobic process that volatilize at 550 °C, used as an indicator of active micro-organisms, expressed in mg/l
SRT	Solids retention time, the time it takes for solids to pass through the treatment system, measured in days

TN	Total Nitrogen, the total amount of nitrogen, expressed in mg/l
TP	Total Phosphorus, the total amount of phosphorus in the liquid, expressed in mg/l
TSS	Total Suspended Solids, the total amount of solids in the water, containing both organic and inorganic constituents, expressed in mg/l
VSS	Volatile Suspended Solids, the portion of solids that volatilize at 550 °C, an indicator of active micro-organisms expressed in mg/l

1 INTRODUCTION

Wastewater treatment plants on ships have inherent complications compared to land based applications; space is limited, the raw waste water is high in biological content and treatment facilities need to be able to handle even toxic loadings, while producing high quality effluent. On the other hand, some design aspects are simplified such as environmental factors like rainfall and external leaching do not have to be taken into account, thus flow patterns are more consistent.

The commissioner of this thesis, Royal Caribbean Cruises Ltd., is the world's second largest cruise ship operator as the parent company of five different cruise line brands. The technical branch office in Turku offers consultation for different projects and is overseeing the design of the latest ship for TUI Cruises, a joint venture between Royal Caribbean and TUI AG (a German travel company).

The purpose of this thesis was to determine the biological loading and hydraulic flow of waste water streams generated on a cruise vessel and the capacities of different equipment required for the treatment of the waste, such as tank volumes and aeration requirements. In order to calculate required dimensions for the treatment plant equipment and processes, the suppliers usually make so called mass balance charts to estimate how much wastewater is introduced into the system and how the pollutants are removed at certain steps of the process. The mass balance charts are the most important design tools as the configurations and estimations can be compared between suppliers. However these estimations can vary significantly, for example in the TUI New Building Project "BluMotion" cruise ship one of the competing companies was challenged due to inconsistencies in the mass balance. The goal of the work was to provide a generic scalable mass balance tool that is based on measured flow and pollutant values from several ships currently sailing.

Wastewater in a cruise vessel originates from several sources. Depending on the source of the influent it has very different characteristics in terms of biological content and flow. In order from largest to smallest in terms of volumetric flow rate the sources are accommodation water gray, galley gray water ("galley" = large, industrial kitchen), laundry gray water, black water (from toilets and hospitals), as well as so called reject waters that are formed in the dewatering process of food waste and bio residue. Accommodation gray water is used to dilute other streams, such as laundry water that can contain toxic chemicals or have a very high biological loading like reject waters. This is achieved by sequencing the feed into the process, so that stored accommodation water is mixed in for dilution.

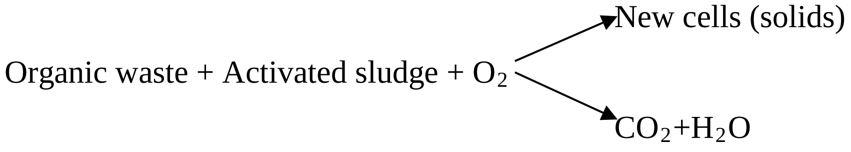
2 WASTEWATER TREATMENT ON CRUISE VESSELS

2.1 Treatment Methods

The treatment of wastewater is a mixture of physical, chemical and biological processes. For a normal land based wastewater treatment plants the levels of treatment are presented in Table 1. Since a cruise ship does not have the space to house as many process steps, especially sedimentation ponds or other solutions requiring large areas. Many of the processes are grouped together, for instance preliminary and primary treatment steps are usually incorporated into a single filter and dissolved air flotation is commonly used to save space instead of sedimentation.

In all systems prior to biological treatment the wastewater is mixed and screened for large solids and plastics. The mixing can take place either before or after the screening phase depending on the installation. Disinfection of the effluent on modern cruise ships is most commonly handled with UV radiation to kill the bacteria. Chlorine could also be used, albeit with very stringent discharge requirements due to environmental concerns. The UV method requires no addition of potentially environmentally toxic disinfection chemicals, but consumes more energy.

The biological process is the heart of most treatment systems. It is the most efficient way of removing soluble organic matter from the wastewater. The biological process is controlled by the conversion processes of biological growth, hydrolysis and decay. In biological growth soluble organic matter is oxidized by micro-organisms, mostly bacteria, fungi and protozoa, to carbon dioxide, water and new cells. (Henze, Harremoes, la Cour Jansen & Arvin 2002.)



Initially only a part of the organic matter is in a soluble and easily biodegradable form. Hydrolysis converts the larger organic molecules to smaller, easily biodegradable forms. The hydrolysis process is slower than biological growth and thus it is usually the limiting factor of the biological treatment process. When the micro-organisms decay their amount is not reduced, but the dead cell mass is hydrolyzed again into slowly biodegradable matter that causes new growth. (Henze et al. 2002.)

In activated sludge plants the sludge is recycled continuously to keep the active biomass at a selected concentration in the tank. As the solids from the biological growth process and the inert solids from the influent water gradually build up, some of them have to be removed periodically from the recycling line to maintain a constant MLSS concentration. If the concentration rises too high, solids may end up in the effluent line. (Tchobanoglous, Burton & Stensel. 2003.)

The two main types of biological treatment processes currently in use on ships are the membrane bioreactor (MBR) and moving bed biofilm reactor (MBBR). The technologies are presented in more detail in the following chapters.

TABLE 1. Levels of wastewater treatment of a conventional treatment plant. Adapted from Tchobanoglous et al. 2003.

Treatment level	Description
Preliminary	Removal of large constituents, rags, sticks, floatables, grit, grease and plastics (discharge of plastics is strictly prohibited)
Primary	Removal of a portion of suspended solids and organic matter by filtration, sedimentation or chemical addition
Secondary (with or without nutrient removal)	Biological removal of biodegradable organic matter and suspended solids by activated sludge or attached growth solutions
Tertiary	Removal of residual suspended solids usually by granular medium filtration or microscreens. Disinfection is also typically a part of tertiary treatment.
Advanced	Removal of dissolved and suspended materials remaining after normal biological treatment when water is required for various reuse applications.

2.2 Nitrogen Removal

As nutrient removal has been a requirement in land based treatment systems for already some time, it is gradually making its way to onboard installations with new regulations calling for more stringent limits for nitrogen and phosphorus. Especially vulnerable sea areas like the Baltic Sea and the Alaskan area are under special attention. Different areas of the Baltic Sea have different limiting nutrients for algal growth with nitrogen and its derivatives being predominantly limiting in the southern areas around the Gulf of Finland and the archipelago, whereas phosphorus is the limiting nutrient in the Bothnian Bay (Uusitalo et al. 2007).

Biological nitrogen removal takes place in three distinct reactions that require different conditions to take place. Ammonification is the breakdown of organic nitrogen to ammonium (NH_4). Followed by nitrification, the biological oxidation of ammonium (NH_4) to nitrite (NO_2) and finally to nitrate (NO_3). Nitrification is performed by aerobic bacteria, whereas ammonification can take place under both aerobic and anaerobic conditions. Especially the bacteria that perform nitrification are slow growing and vulnerable to environmental changes, thus longer solids retention times (SRT) are used to achieve complete nitrification. Denitrification is the reduction reaction of nitrate (NO_3) into molecular nitrogen gas (N_2). Denitrification takes place under anoxic conditions, where the bacteria are able to utilize oxygen bound to the nitrate (NO_3) releasing the inert nitrogen gas to the atmosphere. The reactions are shown below. (van Haandel & van der Lubbe. 2012, 108-110.)

Ammonification:
RNH_2 (organic nitrogen) + $H_2O + H^+ \rightarrow ROH + NH_4^+$ (ammonium ion)

Where the R is used to express the various hydrocarbon chains the nitrogen can be attached to.

Nitrification:
$NH_4^+ + O_2 \rightarrow NO_2^-$ (nitrite) + $H_2O + 2H^+$
$NO_2^- + 2O_2 \rightarrow NO_3^-$ (nitrate) + $H_2O + 2H^+$

Denitrification:

Organic matter + H^++NO_3^- → N_2 (nitrogen gas) + H_2O

2.3 Phosphorus Removal

Phosphorus is most commonly removed by chemical precipitation followed by sedimentation or flotation. Phosphorus in wastewater is predominantly in the form of orthophosphate ions (PO_4^{3-}). Metal ions such as aluminium (Al^{3+}) or iron (Fe^{3+}) combine with the soluble orthophosphate ions (PO_4^{3-}) to form an insoluble precipitate ($AlPO_4$ or $FePO_4$) that can be removed from the water by physical means. Also a variety of polymers can be used to precipitate phosphorus. (van Haandel & van der Lubbe. 2012, 239; Tchobanoglous et al. 2003, 501-505)

2.4 Membrane Bioreactors

Membrane bioreactors (MBR) utilize an activated sludge process combined with micro or ultrafiltration membranes to separate the clean water from the biomass. The biggest advantage of membrane plants is their small size and good quality effluent with less process steps than in alternatives. The major disadvantages are higher capital cost and the sensitivity of the membranes, as they are prone to permanent fouling. Especially correct dissolved oxygen level is important as too low DO can cause bulking sludge and block the membranes, as has been the case on some Royal Caribbean ships utilizing this technology. (Tchobanoglous et al. 2003, 854-856.)

The membrane cartridges can either be submerged in the reactor as seen in Figure 1, or they can be in external units as in Figure 2, which significantly increases the pumping energy required. The main advantage of having the membranes in an external case is the ease at which they can be removed for inspection and cleaning. On the other hand an advantage of submerged membranes is that the effluent (permeate) can be siphoned through either by gravity or a slight under pressure, consuming less energy. Only a handful of submerged membrane bioreactors have been installed on ships of over 1000 passengers and the technology is improving with each installation as valuable lessons are learned from operator experiences. In a submerged setup the tank has to be drained prior to inspection and cleaning. The membrane surfaces in a submerged setup are kept clean by the turbulent motion of air bubbles, which are discharged at the bottom of the membrane stacks. In an external setup the membranes are kept clean by the high cross-flow inside the membrane unit. Frequent back-washing is also required. (Sutton. 2006.)

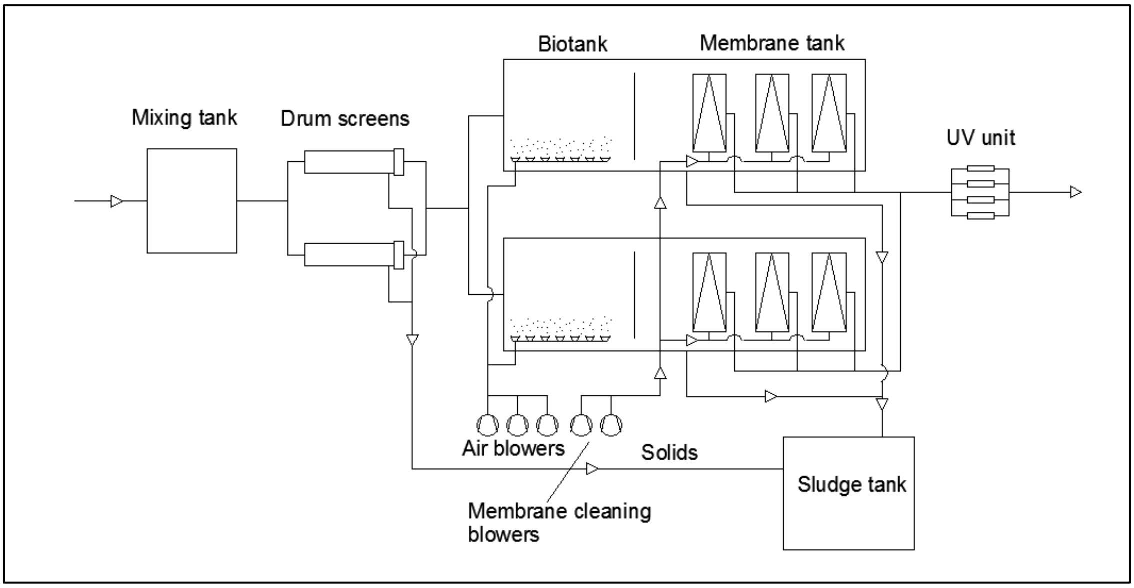


FIGURE 1. Schematic of a typical membrane bioreactor treatment system with submerged membranes.

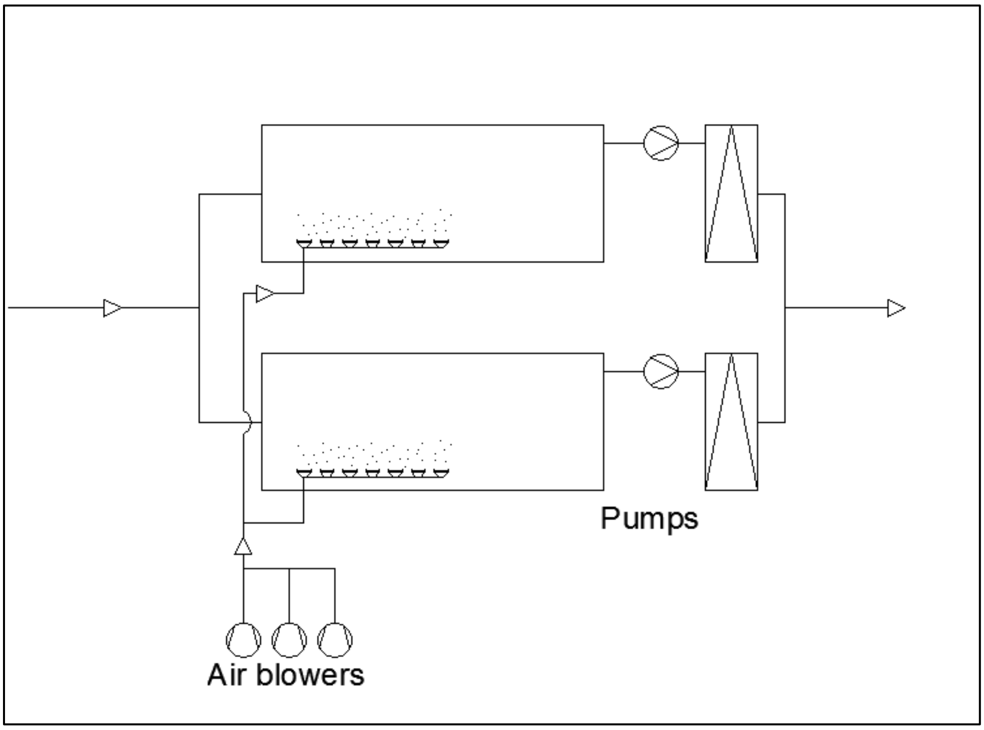


FIGURE 2. Membrane reactor configuration with external membranes.

The mixed influent is pumped to the primary screens from where it goes to the aerated bioreactor. There the biological process starts to consume the organic matter. As the solids build up in the bioreactor, a desludging process is carried out periodically by removing bio residue from the tank when the MLSS concentration reaches a set limit. Usually it is kept in the 12000 mg/l to 15000 mg/l range (Celebrity Eclipse Engineering Crew interview. 2012). The term bio residue here indicates that the solids do not contain any plastics in them as opposed to bio sludge, which can contain plastics.

2.5 Moving Bed Biofilm Reactor

The moving bed biofilm reactor (MBBR) was invented in Norway in the early 1990s. The process is based on providing a large surface area for microbes to grow on inside the reactor, increasing the amount of biomass in the tank without having to increase the size of the basin itself. This is achieved by using carrier elements, an example of which is seen in Figure 4. They are usually made from plastic with complex structures providing large surface areas, on which the bacterial mass grows on to create a so called biofilm. (Tchobanoglous et al. 2003, 952-954.)

Usually in onboard configurations the MBBR is combined with a dissolved air flotation unit and a polishing filter to remove the accumulated solids from the effluent before disinfection and discharge to the sea as seen in Figure 3. This combination will also be used by Scanship for the installation on TUI New Building “BluMotion” vessel; the configuration has been successfully used on many previous installations. (Scanship Technical Specification for TUI NB “BluMotion”. 2012.)

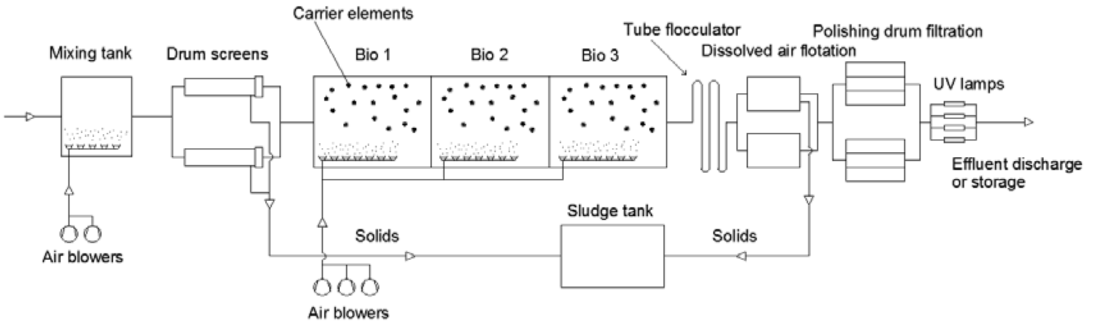


FIGURE 3. Schematic of Celebrity Constellation MBBR treatment plant.

The carrier pieces are kept mobile either by a mechanical mixer or the aerators. When considering the type of aeration to be used in MBBRs it should be noted that the tank is not easy to empty due to the carrier elements mixed in the water. Thus a coarse bubble aeration system is a better choice due to lower maintenance requirements and the bubbles have stronger buoyancy to keep the elements moving. As a consequence more air is needed to aerate the tank, since the oxygen transfer efficiency of larger bubbles is lower than for smaller ones. (van Haandel & van der Lubbe. 2012, 85.)

The maximum filling ratio or the maximum fraction of carrier pieces in the tank is around 67%-70% (Rusten, McCoy, Proctor & Siljudalen, 1998; Rasmussen, 2009). Higher percentages could lead to lowered performance due to limited movement of carrier elements and problems in oxygen transfer, causing unwanted anoxic zones in the tank. This was probably the initial cause of bad treatment performance on board RCCL’s Oasis of the Seas, where the filling ratio was increased without increasing aeration capacity. As a consequence the movement of the carriers was hampered and anoxic dead spots were formed in the reactor, causing the sludge to bulk inside the reactor.

Another important design aspect is the organic loading per square meter of carrier element surface area. According to Rusten et al (1998) the average level should be kept below 20 g of BOD_5/m^2 to achieve adequate organic matter reduction. For the TUI NB “BluMotion” project the value is 8,7 g of BOD_5/m^2 with a BOD load of 1175 kg/d and a total surface area of 134400 m^2. The carrier elements used by Scanship have a very high specific surface area of 800 m^2/m^3. (Scanship Technical Specification for TUI NB “BluMotion”. 2012.)

FIGURE 4. Biofilm carrier element used by Headworks with the attached bacterial mass visible. Source, Headworks USA

2.6 Chemicals in Onboard Wastewater Treatment

Chemical precipitation is used to remove fine particulates and colloidal matter from the wastewater by clumping up the particles to create larger flocs that can be removed by flotation or sedimentation. Their function is based on destabilising colloidal particles, which normally are free moving and insert repulsive force towards other colloids. The chemicals destabilise the colloids, making the aggregation of particles into larger flocs possible upon collision. (Tchobanoglous et al. 2003)

In land based treatment plants the flocculation chemicals are often used to improve the performance of a settling pool but due to the space limitations on ships this phase is replaced with a dissolved air flotation unit. The flocculated particles are floated to the surface of the unit by the buoyancy of air bubbles, which are diffused from the bottom of the tank. The floating solids are then removed physically by a skimmer and transported for further solids treatment. Common chemicals for flocculation include metal salts like alum, ferrous sulphate and synthetic polymers like polyacrylamide. These synthetic polymers are also commonly used in decanters to improve the dewatering process. (Tchobanoglous et al. 2003; Scanship Technical Specification for TUI Blumotion. 2012.)

In case of foaming in the bioreactor, sprinklers are first used to spray cleaned effluent on the mixed liquor to keep the foam down. In case it is not effective, defoaming chemicals can be used to control the foaming before the cause can be identified and corrected. Membrane filtration units also need to be cleaned periodically by a so called cleaning-in-place (CIP) system, which backwashes the membrane plates or tubes by pumping sodium hypochlorite (bleach) through them in a reverse direction. (Jokela. 2012)

Sodium hydroxide (NaOH) is used to keep the pH of the biological process around neutral (pH 7). Especially the nitrification reactions and food wastes (especially citrus fruits) tend to lower the pH of the bioreactor, causing less optimal conditions for the microbes and disturbances in the treatment. (Jokela. 2012; Henze et al. 2002, 92.)

3 WASTEWATER FRACTIONS

3.1 Gray Water

Gray waters generated in cruise ships can be divided into accommodation water, laundry water, and galley water. Accommodation water is typically very dilute in terms of BOD and solids, since it originates from sinks, showers and baths. Accommodation water also has the highest volume, thus it is used for diluting stronger streams.

Laundry water also has a rather low level of BOD, but it may contain toxic cleaning chemicals that can harm the microbial organisms of the bio reactor and cause foaming in the reactor. Water used in the laundry is typically collected from the ship’s air conditioning system. As the air is cooled its ability to retain water is diminished and condensate is formed. The condensate has high enough purity to be used in laundry applications, although it can have varying pH and chloride concentration depending on the ambient conditions, for instance salt water sprays can be mixed with the inlet air and cause a higher concentration of chlorides. Cooling coils are also typically made of copper that can dissolve into the condensate water giving it an elevated copper concentration compared to land applications. (Salama. 2012.)

Galley water originates from the galleys (=kitchens) of the ship, from the dishwashers, sinks and floor gutters. As seen in Table 2, it is characterized by a very high organic content level, in both soluble (BOD) and particulate (TSS) form and it is produced in large volumes making it the largest single source of organic matter into the treatment system.

Galley water and food waste reject water is also treated with a grease separator to remove fats, oils and greases (FOG). These substances generally inhibit microbial growth, cause foaming, as well as promote the growth of filamentous bacteria, which in turn creates problems with sludge handling. (Chipasa & Mdrzycka, 2006)

3.2 Sewage or Black Water

Black water from toilets and latrines on ships differs from the sewage generated in conventional toilets, since it is flushed with a vacuum system, using only about 1,2 litres of water per flush (Evac Oy Technical Brochure, 2012). This causes the water to be heavily concentrated with biological matter, but it is produced at lower volumes. Black water is often used to start up bio reactors, since it provides a lot of easily biodegradable matter for the microbes. The ship is divided into several independent systems, where one vacuum generating system serves one main fire zone. The vacuum station typically has a double vacuum pump for redundancy connected to the collecting tank, in which the matter is sucked by the under pressure from the toilets. When the toilet is flushed, the batch of excreta moves for a certain distance in the system, with each consecutive flush the batches are sucked closer to the collection station until it reaches it. From the collecting tank the black water is further pumped to the AWP system.

3.3 Reject Waters

Reject water is generated when bio residue and food waste is dewatered for further drying and ultimately incineration. The excess water that is separated from the bio mass is called reject water. Usually they are referred to as food waste reject water and sludge reject water, depending on the source. Food waste reject water is generated in very small amounts but it is so saturated by organic matter that it typically accounts for 25-30% of the total biological loading of the system. The sludge reject water drained from the less concentrated sludge/bio residue has a lower BOD concentration with most of the matter in an easily biodegradable form.

Food waste is typically first treated with a rotating press to increase the solid content. The downside of the press is that the reject water gets increasingly saturated with organic matter the harder the food waste is pressed to drain the water from the solids, but on the other hand if the food waste is not pressed enough the solids content of the waste to be dried will be too low. Depending on the configuration of the vessel, the pressed solids can be further treated in a rotating decanter and dried by introducing hot air into the mass and mixing it violently. The dried solids will be finally disposed of by incineration. Bio residue is typically only treated in a rotating decanter before drying and incineration. All the water generated in the dewatering process steps is led back to the AWP system. The quality of the reject water depends heavily on the performance of the decanter as correct polymer dosage can drastically reduce the amount of organic matter returning to the AWP.

The average values for the different wastewater fractions are presented in Table 1. The values for average flow are estimated for a ship of 3820 passengers and crew, which is the planned size for the vessel currently under development. The data has been collected from several vessels in the Royal Caribbean International and Celebrity Cruises fleets.

TABLE 2. Average wastewater influent characteristics for a ship of 3820 passengers and crew.

Wastewater stream	Average flow m3/d	Average BOD mg/l	Average TSS mg/l	pH range*
Accommodation water	458	370	100	6-7
Galley water	175	2000	2500	3-4
Laundry water	95	200	100	7-9
Black water	68	2300	1870	7-8
Food waste reject water	7	40000	23000	<3,5**
Sludge reject water	19	10000	1000	N/A
Total influent	**822**	**1350**	**1000**	**~7**

*pH values from Evac Oy data on Voyager class ships.

**Estimation

4 MARINE WASTEWATER DISCHARGE LEGISLATION

4.1 International Maritime Organization

The International Maritime Organization, IMO, is a specialized United Nations agency concerned with maritime safety and pollution. The organization has a total of 170 member states and three associate members. Legislation adopted by IMO is implemented and enforced by member state governments. The Marine Environment Protection Committee (MEPC) of the organization deals with environmental aspects of shipping such as sewage disposal and oil dumping. It is also concerned with protecting so called Special Areas and Particularly Sensitive Sea Areas, in which the Baltic Sea also belongs to. (Brown, N. 2011.)

The most important resolution concerning environmental pollution is MARPOL 73/78. Annex IV defines the wastewater discharge regulations. In the resolution sewage is defined to be drainage and other waste from any form of toilets, urinals, and WC scuppers or drainage from medical premises (dispensary, sick bay, etc) originating from wash basins, sinks or scuppers in these areas. Also drainage from spaces containing living animals or whenever other wastewaters are mixed with the aforementioned it is considered sewage. Note that food waste in itself is not considered sewage, although it has a very high biological loading. (MARPOL 73/78 Annex IV.)

In terms of sewage waste the legislation states that untreated waste can be discharged if the vessel is sailing 12 nautical miles away from the nearest coast, if discharging at a moderate rate and the vessel is moving at a speed of no less than 4 knots. Further the discharged effluent shall not produce any visible floating solids or discoloration of the surrounding water. Comminuted and disinfected wastewater can be discharged when the vessel is at least 4 nautical miles away from the coast. If the ship is operating an approved treatment plant producing effluent according to the emission limits seen in Table 3 the wastewater can be discharged without limitations, unless it is prohibited by national law or the vessel is operating in a special zone. (MARPOL 73/78 Annex IV.)

TABLE 3. MEPC.159(55) Wastewater pollutant limits.

Parameter	Minimum Value During Test Period	Maximum Geometric Mean During Test Period	Maximum Value During Test Period
Thermotolerant Coliform*	N/A	100 per 100 ml	N/A
BOD5	N/A	25 mg/l	N/A
Total Residual Chlorine	N/A	N/A	0,5 mg/l
pH	6	N/A	8,5
Total Suspended Solids (TSS)	N/A	35 mg/l	N/A
COD	N/A	125 mg/l	N/A

*The expression Thermotolerant Coliform is used instead of Faecal Coliform to indicate that not all coliform bacteria are of faecal origin.

4.2 HELCOM Amendment to IMO Regulations

Under the proposal of the Baltic Marine Environment Protection Commission (commonly known as HELCOM or Helsinki Commission), the Baltic Sea will be the first to be designated as a special area in terms of sewage waste. The regulation completely prohibits the discharge of untreated wastewater from passenger ships. If the ship wishes to discharge any wastewater, it must be treated with an approved system. The water has to in addition to IMO wastewater standards comply with stringent nutrient limits as current IMO regulations do not have any limits for nutrient emissions.

If the amendment will pass in its current form it will set the following limits for treated wastewater in the Baltic area. Nitrogen concentration under 20 mg/l (or at least 70% reduction) and phosphorus concentration under 1,0 mg/l (or at least 80% reduction). The resolution will come into effect for newly built ships from the beginning of 2016 and for existing ships beginning of 2018. (Helsinki Commission, Tenth Meeting, 2011.)

4.3 Alaskan Legislation

Due to the unique and vulnerable nature of Alaska, the state has enacted special legislation regarding wastewater disposal compared to other areas. Discharge of untreated wastewater in Alaskan waters is completely prohibited. Treated wastewater can be discharged if the vessel is travelling at a speed of no less than 6 knots and the ship has to be at least one nautical mile away from the nearest shore. In certain areas even the discharging of treated effluent is prohibited, thus the relatively clean effluent must be stored onboard until the ship is in such an area where it can discharge again or where it can pump the effluent on shore to a reception facility. Furthermore the legislation has some different limits compared to the IMO standards. The Alaska Legislation imposed the first stringent areal discharge limits for cruise ships and it has become the basis for dimensioning wastewater treatment plants. The effluent limits can be seen in Table 4. (33 USCA § 1901 NOTE, Title XIV, Certain Alaskan Cruise Ship Operations. 2000.)

Moreover the law enacted in 2010 states limits for ammonia, copper, nickel and zinc, which are made AWP supplier specific, since different kinds of wastewater treatment systems remove these pollutants at varying efficiency (2010 Large Commercial Passenger Vessel Wastewater Discharge General Permit Information Sheet, 2010). This received significant criticism from outside environmental parties such as Friends of the Earth and Campaign to Safeguard America’s Waters, who sued and won the case against the Alaska Department of Environmental Conservation. The main argument was that the new regulation did not encourage ship operators to use the best available technologies. Thus it is very likely that this discharge permit will be altered in the near future. (Court Orders Alaska to Fix Cruise Ship Discharge Permit (Press release). 2012.)

TABLE 4. Pollutant limits for the Alaskan area.

Parameter	Minimum Value	Maximum Monthly Average	Daily Maximum
Faecal Coliform	N/A	14 CFU/100ml	43 CFU/100ml
BOD5	N/A	30mg/l	60mg/l
Total residual chlorine	N/A	N/A	10µg/l
pH	6,5	N/A	8,5
Total Suspended Solids (TSS)	N/A	N/A	150mg/l

5 MASS BALANCE MODEL

5.1 General

The mass balance model introduced in this thesis is intended to help in the designing phase of the ship to check values and give guidelines to the dimensioning of the treatment plant as well as making sure that the plant is fit for purpose. Also it is helpful when comparing and combining the mass balance calculations of different companies, which are perhaps supplying different parts of the complete waste handling system. For instance in the “Blumotion” project the dry side, including driers and incinerators will be provided by a different company than the wet side, the biological treatment system itself.

In Appendix 1 and example of the model is given with the passenger and crew capacity of 3820. The different wastewater fractions are given with estimated hydraulic flow, biochemical oxygen demand, chemical oxygen demand, total suspended solids, total nitrogen and total phosphorous. The amount of passengers can be inputted into the model to calculate wastewater amounts for different sized ships. Two main design aspects included in the model are aeration capacity required and the size of the biological reactor. The reactor volume is calculated only for the membrane bioreactor.

The data for the model was gathered from several ships in the Royal Caribbean International and Celebrity Cruises fleets. A large amount of data was acquired from the Celebrity Solstice class vessels, which have around 4300 passengers and crew. The ship is operating a membrane bioreactor wastewater treatment system. Other major inputs were the Voyager class with a slightly higher passenger capacity as well as the Oasis of the Seas, which both have a moving-bed biofilm reactor setup. Oasis is also the largest cruise ship in the world with about 8400 passengers and crew. To reach comparable values from the different sized ships, the flows were calculated as cubic meters per passenger per day. Biological and total suspended solids loading are calculated as kilograms per passenger per day.

5.2 Assumptions

Measured water flow rates and pollutant concentrations are used where possible. The measurements for galley gray water were very inconsistent between different ships, thus some of the measurements were omitted from the average calculation. The concentrations from the Evac Technical Specification (Jokela. 2012) were used as a reference and values of 2000 mg/l of BOD and 2500 mg/l of TSS (for 3820 passengers) were estimated for the model. Also the flow amounts for the different gray water fractions are estimated, since usually only the total gray water flow rate is measured. Furthermore the nutrient carryover of from the sludge reject water could not be determined due to lack of data.

About 10 mg/l of the influent total nitrogen is deposited into the wasted bio residue (The Water Planet Company. 2012). What is not released in the effluent is assumed to be converted into nitrogen gas and released into the atmosphere by the denitrification process. The phosphorus is assumed to be taken up by the bacteria as well as removed by precipitation, ending up in the waste bio residue.

Generally the ratio of passengers compared to crew members affects water consumption, but the difference was not taken into account in this study, since the effect is very minute. The ratio of passengers per crew on Royal Caribbean and Celebrity vessels vary from 2,5 to 3,2.

5.3 Aeration Capacity Calculations

As for any other wastewater treatment system, the aeration blowers are the most energy consuming components of the facility and optimising their output can bring considerable savings. Although modern blowers can operate at varying capacities thanks to variable frequency controller systems coupled with dissolved oxygen sensors, the air flow can be regulated on the fly according to demand. (Tchobanoglous et al. 2003, 1706-1707.) But in order to dimension the blowers correctly the oxygen and thus air requirement of the system must be evaluated.

Depending on the size of the bubble the oxygen transfer efficiency can vary considerably. Small ("fine") bubbles are much more efficient than larger ("coarse") bubbles as seen in Table 5. Only diffused aerators are considered in this study, as they are the only ones feasible for on-board installations, with a small size and high capacity. Standard oxygen transfer efficiency is given as a percentage in tap water in standard conditions for comparison as the conditions at different wastewater treatment plants vary significantly and cannot be compared directly.

TABLE 5. Oxygen transfer efficiencies of some types of diffuser systems. Adapted from Tchobanoglous et al. 2003.

Diffuser type	SOTE* (%)
Fine bubble ceramic grid	25-37
Fine bubble membrane grid	22-29
Coarse bubble	9-13

*Standard oxygen transfer efficiency. Conditions: tap water 20 °C, atmospheric pressure and initial dissolved oxygen level 0 mg/l.

The membrane plant is able to operate at a very high mixed liquor suspended solids (MLSS) concentration of around 10,000 mg/l. In other words also the concentration of active micro-organisms in the aeration tank is very high, consequently also the solids retention time (SRT) or the average time that solid matter takes to go through the system is very high, around 10 days compared to traditional activated sludge plants where it is typically around 5 days. The kinetic growth coefficients used in the calculation are given in Tchobanoglous et al. (2003) pages 706-707. Also the substrate concentrations are measured in BOD_5, as opposed to biodegradable COD (bCOD) used in the book as the source data is too limited to calculate the biodegradable and non-biodegradable components separately. The dissolved oxygen level should be maintained at a minimum of 2,0 mg/l to ensure aerobic activity. (Tchobanoglous et al. (2003).

TABLE 6. Parameters for MBR air flow calculation.

Parameter	Value
Q (flow)	823 m^3/d
Design SRT	10 days
Design MLSS	10,000 mg/l
S_0 (influent BOD)	1350 mg/l
S (effluent BOD)	23 mg/l
Dissolved O_2 level	2,0 mg/l
α –factor	0,5*
ß –factor	0,95*
F	0,9*
k_d	0,18*
k_{dn}	0,12*
f_d	0,15*
Y (yield)	0,4 g VSS/g BOD*
Y_n (yield for nitrogen)	0,12 g VSS/ g NO_x*
T (wastewater temperature)	30 °C**
NO_x	45,6 mg/l***

*From Tchobanoglous et al. 2003. (p. 706-707) and van Haandel & van der Lubbe. 2012. (p. 339). Typical values corrected for the right system temperature.

**From ship visit on Celebrity Eclipse, wastewater temperature was stable between 30°C and 32°C, readings taken from the bioreactor tank.

***Amount of NH4 nitrified, 80% of total nitrogen.

Wastewater parameters are taken from the mass balance model in Appendix 1 for 3820 passengers and crew. All formulas in this chapter are from Tchobanoglous et al. (2003). The formulas are meant for conventional activated sludge plant design, but the equations are assumed to be applicable also for a submerged membrane plant, since the removal of soluble BOD must take place in a similar manner as in a conventional plant as the membranes will not filter it out. The equations use total Kjeldahl nitrogen to calculate the amount of ammonium nitrified, since this data was not available, it is assumed that total nitrogen can be also used. Other terms explained in more detail as they are introduced in the calculations.

First the amount of biomass generated ($P_{X,bio}$) as kilograms per day of volatile suspended solids must be calculated with the following equation.

$$P_{X,bio} = \frac{QY(S_0 - S)}{1 + (k_d)SRT} + \frac{(f_d)(k_d)QY(S_0 - S)SRT}{1 + (k_d)SRT} + \frac{QY_n(NO_x)}{1 + (k_{dn})SRT} \tag{1}$$

Where k_d and k_{dn} are endogenous decay coefficients for organic matter removal and denitrification respectively. It tells how much cell mass is lost due to cell maintenance, cell death and predation. The coefficient f_d remarks the amount of cell mass that stays as non-biodegradable debris after cell death.

$$\begin{aligned} & P_{X,bio} \\ & = \frac{823m3/d * 0{,}4g/g * (1350 - 23)g/m3}{1 + (0{,}18g/g * d) * 10d} \\ & + \frac{(0{,}15g/g)(0{,}18g/g * d) * 823m3/d * 0{,}4g/g * (1350 - 23)mg/l * 10d}{1 + (0{,}18g/g * d) * 10d} \\ & + \frac{823/d * 0{,}12g/g * 45{,}6mg/l}{1 + (0{,}12g/g * d) * 10d} = 200189{,}00g/d = 200{,}19kg/d \end{aligned} \tag{2}$$

The next step is to calculate the oxygen demand of the biological organisms.

$$R_0 = Q(S_0 - S) - 1{,}42 * P_{X,bio} + 4{,}33 * Q(NO_x) \tag{3}$$

Where, R_0= Total oxygen requirement.

$$\begin{aligned} & R_0 = 823m3/d * (1350 - 23)g/m3 - 1{,}42 * 200{,}19 * 10^3 g/d + \\ & 4{,}33 * 823m3/d * 45{,}6g/m3 = 970{,}35\ kg/d \text{ or } 40{,}43kg/h \end{aligned} \tag{4}$$

In the next equations the oxygen saturation concentration is corrected for the wastewater temperature and depth of the tank. Also if the plant would be situated in an elevated location, then it would be corrected here as well but as the plants in ships are at sea level there is no need for elevation correction.

First the ambient pressure is determined in meters of clean water.

$$P_{atm,H\ (in\ meters)} = \frac{P_{atm,H\ (in\ kilo\ Pascals)}}{\gamma} \tag{5}$$

Where, $P_{atm,H}$= atmospheric pressure at height H and γ= specific weight (kN/m3)

$$P_{atm,H\ (in\ meters)} = \frac{101{,}325\ kN/m^2}{9{,}789\ kN/m^3} = 10{,}35m \tag{6}$$

Equation (7) is used to obtain the actual oxygen saturation concentration. Assuming that the percent oxygen concentration leaving the aeration tank is 19% and the depth of the tank is 5 meters with the diffusers 0,5 meters above the bottom, giving an effective depth of 4,5 meters.

$$C_{\bar{s},T,H} = C_{s,T,H}\left(\frac{1}{2}\right) * \left(\frac{P_{atm,H} + P_{w,eff.depth}}{P_{atm,H}} + \frac{19}{21}\right) \tag{7}$$

$C_{\bar{s},T,H}$ =Actual saturation concentration corrected for depth of tank and oxygen concentration of air leaving tank.

$C_{s,T,H}$ =Oxygen saturation concentration at temperature T and altitude H, here 7,54mg/l.
$P_{w,eff.depth}$ =Effective depth of aerators; tank depth subtracted by the distance of the aerators from the bottom of the tank.

$$C_{\bar{s},T,H} = 7{,}54\,mg/l * \left(\frac{1}{2}\right) * \left(\frac{10{,}35m + (5m - 0{,}5m)}{10{,}35m} + \frac{19}{21}\right) = 8{,}82mg/l \tag{8}$$

To convert the rate at which oxygen must be supplied into the system to standard conditions the following correctional factors must be used:

TABLE 7. Correctional coefficients to take into account in aeration capacity. (Tchobanglous et al. 2003 and van Haandel & van der Lubbe. 2012.)

Coefficient	Value (unitless)	Explanation
α	0,5	Oxygen transfer correction factor depends on aeration system, tank geometry and wastewater characteristics. Typical value for membrane systems is 0,5.
ß	0,95	Salinity-surface tension correction factor, typically 0,95 for domestic wastewater.
F	0,9	Fouling correction factor which depends on aeration system used. A typical value for fine bubble diffusers is 0,9. Coarse bubble diffusers have lower values due to better fouling resistance.

The following formula is used to obtain the standard oxygen transfer rate (SOTR) from the actual required oxygen transfer rate (AOTR) calculated in equation (4).

$$SOTR = AOTR\left(\frac{C_{s,20}}{\alpha F\left(ßC_{\bar{s},T,H} - C\right)}\right) * (1{,}024^{20-T}) \tag{9}$$

$$SOTR = 40{,}43\,kg/h\left(\frac{9{,}08mg/l}{0{,}5 * 0{,}9(0{,}95 * 8{,}82mg/l - 2{,}0mg/l)}\right) * (1{,}024^{20-30}) = 100{,}88kg/h \tag{10}$$

Equation (11) is used to determine the density of air (ρ_{air}) at a certain temperature. Ambient air temperature is assumed to be 20 °C or 293,15 K

$$\rho_{air,20°C} = \frac{PM}{RT} \tag{11}$$

P= Atmospheric pressure, 1,01325*10^5 N/m^2
M= Molecular mass of air, 28,97 kg/mol
R= Universal gas constant,8314 Nm/mol*Kelvin
T= Temperature in Kelvin = 293,15K

$$\rho_{air,20°C} = \frac{1{,}01325 * 10^5 \text{ N/m}^2 * 28{,}97 \text{ kg/mol}}{8314 \text{ Nm/mol} * \text{K} * 293{,}15\text{K}} = 1{,}204 kg/m^3 \tag{12}$$

Of which 23,18% by weight is oxygen.

$$1{,}204 kg/m^3 * 0{,}2318 = 0{,}279 kg/m^3 \tag{13}$$

Lastly, knowing the efficiency of the aerators and the density of oxygen in ambient air, the volume of air needed for the process can be calculated as follows.

$$Q_{qir} = \frac{SOTR}{E * 0{,}279 kg/m^3} \tag{14}$$

Q_{qir} = Air flow
E = Efficiency of the diffusers

$$Q_{qir} = \frac{100{,}88 kg/h}{0{,}30 * 0{,}279 kg/m^3} = 1205{,}31\, m^3/h \tag{15}$$

According to van Haandel and van der Lubbe, for plate membranes the amount of air needed for cleaning the membranes is on average 0,4 m^3/h per square meter of membrane surface area. The Kubota plate membrane, also proposed in the Evac Oy specification for the TUI New Building project has a surface area of $290\ m^2/unit$. The specification featured a six unit configuration having a total surface area of $1740\ m^2$, requiring an additional $700\ m^3/h$ of air flow. Finally the required air flow would be around $1900\ m^3/h$. This amount will maintain a $2{,}0\ mg/l$ dissolved oxygen level in the biological process tank and provide enough airflow to scour the membrane surfaces.

A moving bed biofilm reactor on the other hand has a typical design MLSS concentration of around 3000 mg/l and a shorter SRT of 3 days (Rusten, McCoy, Proctor & Siljudalen. 1998, 1083-1089). Furthermore coarse bubble aeration is used, thus oxygen transfer efficiency is lower, around 11%. An α-factor of 0,8 and fouling factor (F) of 0,6 is estimated for the coarse bubble system. The ß-factor stays unchanged as 0,95, since the surface tension and salinity of water stay the same. With these parameters the biomass production and oxygen requirements would be as follows.

$$P_{X,bio} = \frac{QY(S_0 - S)}{1 + (k_d)SRT} + \frac{(f_d)(k_d)QY(S_0 - S)SRT}{1 + (k_d)SRT} + \frac{QY_n(NO_x)}{1 + (k_{dn})SRT} \tag{16}$$

$$P_{X,bio} = 309956{,}24\ g/d = 309{,}96\ kg/d \tag{17}$$

$$R_0 = Q(S_0 - S) - 1{,}42 * P_{X,bio} + 4{,}33 * Q(NO_x) \tag{18}$$

$$R_0 = 814{,}48{,}6\ kg/d\ or\ 33{,}94\ kg/h \tag{19}$$

Taking into account the different correctional factors the oxygen transfer rate is given in equation (20) and the air flow at 11% efficiency in equation (22).

$$SOTR = AOTR\left(\frac{C_{s,20}}{\alpha F\left(ßC_{\bar{s},T,H} - C\right)}\right) * (1{,}024^{20-T}) \tag{20}$$

$$SOTR = 79{,}40\ kg/h \tag{21}$$

$$Q_{qir} = \frac{SOTR}{E * 0{,}279 kg/m^3} \tag{22}$$

$$Q_{qir} = 2587{,}07\ m^3/h \tag{23}$$

In the coarse bubble aeration for the MBBR final air flow is around 2600 m3/h, which is significantly lower than the capacity specified by Scanship (4000 m3/h) for this type of system (Scanship Technical Specification for TUI Blumotion. 2012). It should be noted that the equation used to calculate the air flow is meant for a conventional activated sludge plant, so it should be used only for general guidance if there is not enough data to carry out more complicated calculations. It is assumed that the aeration capacity is linearly dependent on the amount of passengers and thus it can be calculated for ships of given size in the mass balance model. Thus the amount of air needed per person for an MBR and MBBR would be 0,515 m3/h*p and 0,677 m3/h*p respectively.

5.4 Tank Dimensioning

Generally it can be said that the biological process tank volumes needed for moving bed biofilm treatment systems are somewhat smaller than for membrane plants. The volume of an activated sludge treatment tank can be calculated rather easily, but for MBBR systems the design calculations are often proprietary knowledge of the manufacturer, which is not openly published.

There are many different ways to calculate the volume of the aeration basin for an activated sludge plant, but an accurate answer can be reached by calculating it by solids retention time and solids production rate as described in Henze, Harremoes, la Cour Jansen & Arvin (2002, 152).

$$F_{SP} = Y * (S_0 - S) * Q \tag{24}$$

F_{SP}=Solids production rate. Other terms as previously defined.

$$\begin{aligned} F_{SP} &= 0{,}4\,kg\,SS/kg\,BOD * (1350 - 23) * 10^{-3} kg/m^3 * 823 m^3/d \\ &= 420{,}39\,kg\,SS/d \end{aligned} \tag{25}$$

$$V = \frac{SRT * F_{sp}}{X} \tag{26}$$

X=Organic solid content in aeration tank, can be expressed in many ways, here MLSS concentration ($10000\,mg/l\ =\ 10\,kg/m^3$) is used.

$$V = \frac{10\,d * 442{,}0 kg/d}{10\,kg/m^3} = 420{,}39\,m^3 \tag{27}$$

The value can be used to estimate the tank sizes needed for other sized ships as it is assumed that the required size is linearly proportional to the amount of passengers on board a ship. The value from the calculation is close to the one proposed by Evac Oy for the TUI project. In their proposal the total volume of the submerged membrane bioreactor tanks was 400 m3, divided into two independent process tanks (Jokela. 2012). Dividing the volume into several tanks is beneficial, as then the other one can be emptied for cleaning and maintenance without disrupting the whole system.

6 DISCUSSION AND CONCLUSIONS

The purpose of this thesis process was to create a simple and accurate tool for calculating wastewater flows and pollutant loadings. Since the measurement data was produced by several external parties, it is impossible at this point to determine the causes of potential outliers. Thus only some of the values for galley water were omitted due to high discrepancy between two data sets otherwise the data was not manipulated in any way. Also in calculating the loading per person the ships are assumed to be at the maximum designed passenger and crew capacity, which can contribute some error as the ships are almost never at said capacity. It should however still reflect correctly the differences in per passenger quantities between different sized ships, as long as maximum capacities are used always. In reality loading on the treatment system is fluctuating all the time depending on several factors ranging from the restaurant menus to whether the ship is en route or docked.

The accurate calculations related to the MBBRs are unfortunately out of the scope of this thesis and would need further research to find out accurately the air flow required for the treatment process and the sizes of the basins, especially in a multi-tank configuration. The calculations for the submerged membrane reactor were more straightforward and the results should be rather accurate. Other interesting topics to study further could be for instance looking more in depth at seasonal differences in wastewater generation and differences between companies or itineraries.

In Figure 5 the total flow values given by the model are compared against measured values of total wastewater flow. The linear increase used in the model seems to predict the wastewater flow rather accurately with different sized ships. The model gives consistently slightly higher values of total flow compared to measured flows from ships. It should be kept in mind that the flow patterns are changing daily and thus it is difficult to measure an average value that would be accurate every day. The values should rather be used as guidelines of what the flow can be expected to be most of the time under normal operating conditions.

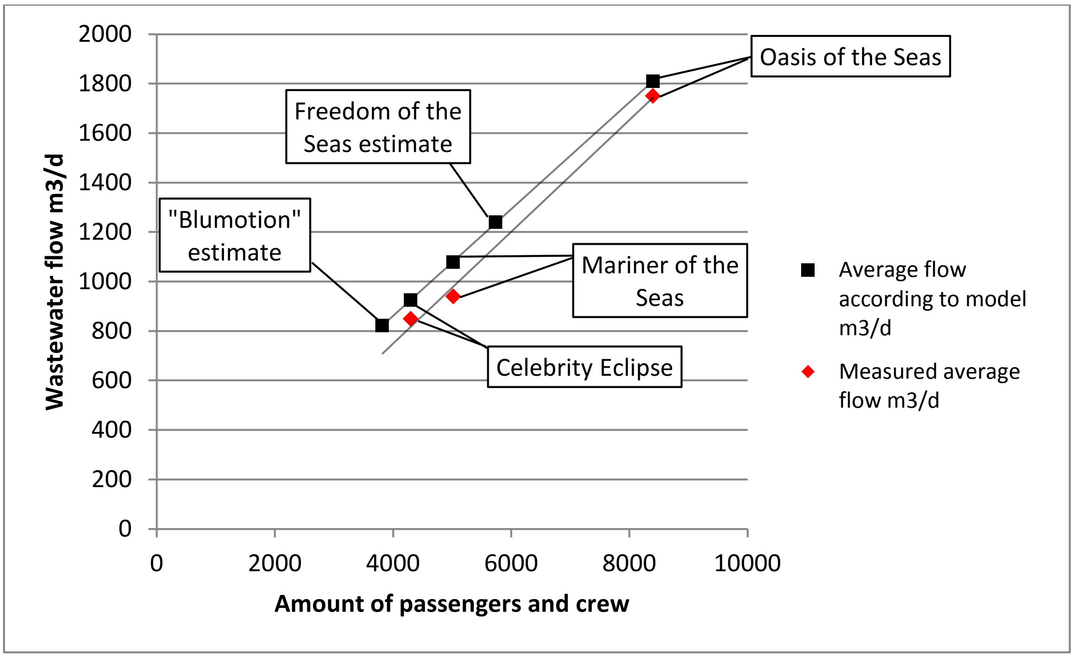


FIGURE 5. Comparison between measured total flow values and model values.

As mentioned the wastewater discharge legislation in Alaska is going to be revised most likely coming into effect next year to promote the use of best available technologies especially in the removal of heavy metals and ammonia. Even though it will only affect the Alaskan area, cruise line companies will often want to comply with those standards regardless of cruise destination to display environmental responsibility and promote the company image. It will be also interesting to see how the stringent nutrient limits of the Baltic Sea will affect cruise line operators and the development of wastewater treatment facilities.

REFERENCES

33 USCA § 1901 NOTE, Title XIV. 2000. Certain Alaskan Cruise Ship Operations.

Alaska Department of Environmental Conservation 2010. 2010 Large Commercial Passenger Vessel Wastewater Discharge General Permit Information Sheet. Read 4.5.2012. http://dec.alaska.gov/water/cruise_ships/pdfs/2010_Cruise_Ship_Info_Sheet_FINAL.pdf

Bitton, G. 2005. *Wastewater Microbiology*. Third Edition. John Wiley & Sons, Inc., New Jersey

Brown, N. 2011. *IMO-The International Maritime Organization*. Presentation. IMO Public Information Services

Celebrity Eclipse Engineering Crew. 2012. Interview.

Chipasa, K.B. & Mdrzycka, K. 2006. *Behavior of lipids in biological wastewater treatment processes*, Journal of Industrial Microbiology & Biotechnology. vol. 33, no. 8 (Aug 2006). Springer, Berlin.

Court Orders Alaska to Fix Cruise Ship Discharge Permit (Press release). 2012. ENews Park Forest. 22.8.2012. Read 12.10.2012. http://www.enewspf.com/latest-news/science-a-environmental/35822-court-orders-alaska-to-fix-cruise-ship-discharge-permit.html

Evac Oy Technical Brochure. 2012. Read 26.6.2012. http://www.evac.com/sites/default/files/attachments/003_Evac_910_toilets_wall_floor.pdf

van Haandel, A.C. van der Lubbe, J.G.M. 2012. *Handbook of Biological Wastewater Treatment*. Second edition. IWA Publishing, London.

Headworks USA. 2012. Moving Bed Biofilm Reactor (MBBR) Technology. Read 27.10.2012. http://www.headworksusa.com/biological-wastewater-treatment/MBBR.aspx

Helsinki Commission, Ninth Meeting. *Outcome of MEPC 62 on the Amendments to MARPOL Annex IV.* Helsinki, Finland. 15.-17.11.2011.

Henze, M. Harremoes, P. Arvin, E. & la Cour Jansen, J. 2002. *Wastewater Treatment, Biological and Chemical Processes.* Third Edition. Springer, Berlin.

Jokela, J. 2012. Technical Specification for TUI Blumotion. Evac Oy. Not published.

Marine Environment Protection Committee resolution MEPC.159(55). 2006. *Revised Guidelines on Implementation of Effluent Standards and Performance Tests for Sewage Treatment Plants.* International Maritime Organization

MARPOL 73/78 Annex IV, International Maritime Organization

Metcalf & Eddy Inc. Revised by Tchobanoglous, G. Burton, F. & Stensel, D. 2003. *Wastewater Engineering, Treatment and Reuse*. Fourth Edition. McGraw-Hill, New York

Rasmussen, V. 2009. *The Kaldnes Moving Bed^{tm} Biofilm Process.* Anoxkaldnes AS (formerly known as Kaldnes Miljöteknologi), Tönsberg, Norway

Rusten, B. McCoy, M. Proctor, R. & Siljudalen, J. 1998. *The Innovative Moving Bed Biofilm Reactor/Solids Contact Reaeration Process for Secondary Treatment of Municipal Wastewater*. Water Environment Research. vol. 70, no. 5, pp. 1083-1089, Water Environment Federation

Salama, H. Senior Superintendent, Royal Caribbean Cruises Ltd. 2012. Notes on wastewater properties. Email message. hsalama@rccl.com. Read 8.12.2012.

Scanship as. 2012. Technical Specification for TUI Blumotion. Not published. Scanship as. Lysaker Torg 12, 1366, Lysaker, Norway.

Sutton. P.M. 2006. *Membrane Bioreactors for Industrial Wastewater Treatment: Applicability and Selection of Optimal System Configuration.* Water Environment Foundation. VA. United States.

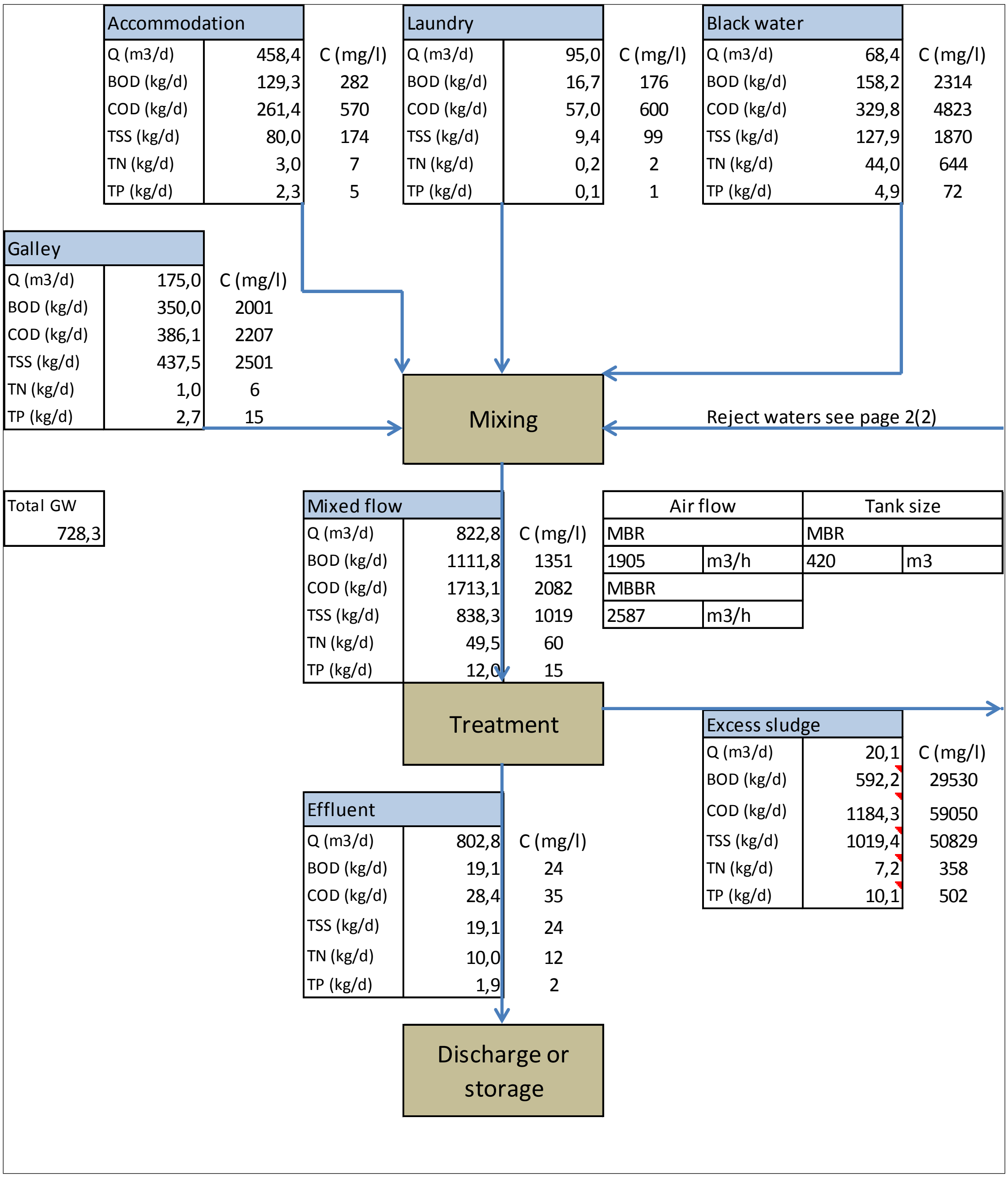
The Water Planet Company. 2012. *Nitrogen Removal from Wastewater, a Primer*. Connecticut, USA. Read 8.11.2012. http://www.thewaterplanetcompany.com/docs/10pdf/Nitrogen%20Primer.pdf

Uusitalo, R. Ekholm, P. Turtola, E. Pitkänen, H. Lehtonen, H. Granlund, K. Bäck, S. Puustinen, M. Räike, A. Lehtoranta, J. Rekolainen, S. Walls, M. Kauppila, P. 2007. *Maatalous Itämeren rehevöittäjänä*. Maa- ja elintarviketalouden tutkimuskeskus MTT. Jokioinen, Finland.

APPENDICES

Appendix 1.

Mass Balance Model 1(2)



Accommodation		C (mg/l)
Q (m3/d)	458,4	
BOD (kg/d)	129,3	282
COD (kg/d)	261,4	570
TSS (kg/d)	80,0	174
TN (kg/d)	3,0	7
TP (kg/d)	2,3	5

Laundry		C (mg/l)
Q (m3/d)	95,0	
BOD (kg/d)	16,7	176
COD (kg/d)	57,0	600
TSS (kg/d)	9,4	99
TN (kg/d)	0,2	2
TP (kg/d)	0,1	1

Black water		C (mg/l)
Q (m3/d)	68,4	
BOD (kg/d)	158,2	2314
COD (kg/d)	329,8	4823
TSS (kg/d)	127,9	1870
TN (kg/d)	44,0	644
TP (kg/d)	4,9	72

Galley		C (mg/l)
Q (m3/d)	175,0	
BOD (kg/d)	350,0	2001
COD (kg/d)	386,1	2207
TSS (kg/d)	437,5	2501
TN (kg/d)	1,0	6
TP (kg/d)	2,7	15

Total GW
728,3

Mixed flow		C (mg/l)
Q (m3/d)	822,8	
BOD (kg/d)	1111,8	1351
COD (kg/d)	1713,1	2082
TSS (kg/d)	838,3	1019
TN (kg/d)	49,5	60
TP (kg/d)	12,0	15

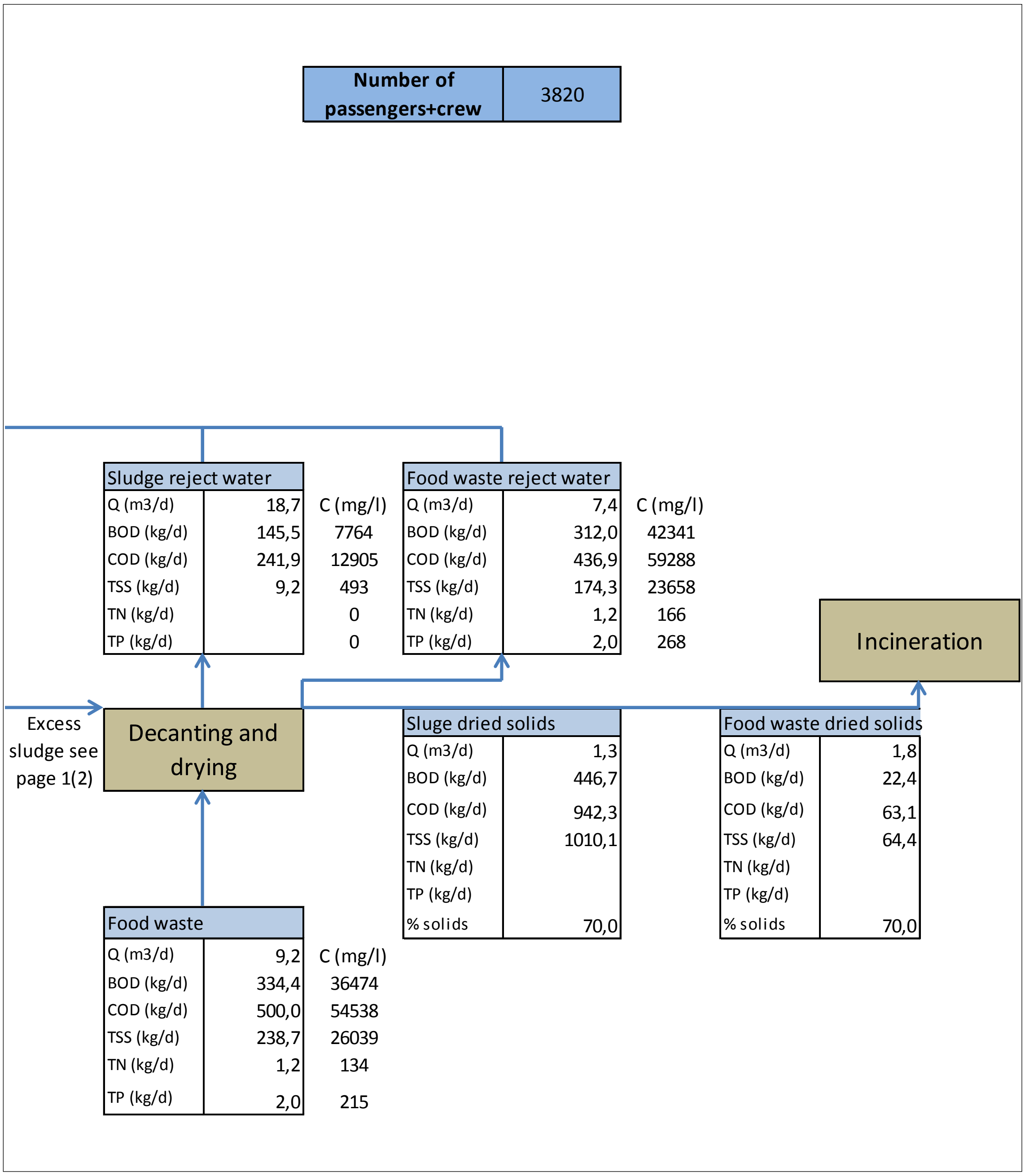
Air flow		Tank size	
MBR		MBR	
1905	m3/h	420	m3
MBBR			
2587	m3/h		

Excess sludge		C (mg/l)
Q (m3/d)	20,1	
BOD (kg/d)	592,2	29530
COD (kg/d)	1184,3	59050
TSS (kg/d)	1019,4	50829
TN (kg/d)	7,2	358
TP (kg/d)	10,1	502

Effluent		C (mg/l)
Q (m3/d)	802,8	
BOD (kg/d)	19,1	24
COD (kg/d)	28,4	35
TSS (kg/d)	19,1	24
TN (kg/d)	10,0	12
TP (kg/d)	1,9	2

(continues)

Mass Balance Model 2(2)



Number of passengers+crew	3820

Sludge reject water		C (mg/l)
Q (m3/d)	18,7	
BOD (kg/d)	145,5	7764
COD (kg/d)	241,9	12905
TSS (kg/d)	9,2	493
TN (kg/d)		0
TP (kg/d)		0

Food waste reject water		C (mg/l)
Q (m3/d)	7,4	
BOD (kg/d)	312,0	42341
COD (kg/d)	436,9	59288
TSS (kg/d)	174,3	23658
TN (kg/d)	1,2	166
TP (kg/d)	2,0	268

Sluge dried solids	
Q (m3/d)	1,3
BOD (kg/d)	446,7
COD (kg/d)	942,3
TSS (kg/d)	1010,1
TN (kg/d)	
TP (kg/d)	
% solids	70,0

Food waste dried solids	
Q (m3/d)	1,8
BOD (kg/d)	22,4
COD (kg/d)	63,1
TSS (kg/d)	64,4
TN (kg/d)	
TP (kg/d)	
% solids	70,0

Food waste		C (mg/l)
Q (m3/d)	9,2	
BOD (kg/d)	334,4	36474
COD (kg/d)	500,0	54538
TSS (kg/d)	238,7	26039
TN (kg/d)	1,2	134
TP (kg/d)	2,0	215