Design optimization of gas-to-liquid biosludge management systems

Rana Mostafa

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Design Optimization of Gas-To-Liquid Biosludge Management Systems

By

Rana A. Mostafa

A Thesis Submitted in partial fulfillment of the requirements for the degree of

Masters of Science in Environmental Engineering

Under the supervision of:

Dr. Emad Imam

Professor of Construction and Architecture Engineering

The American University in Cairo

Fall 2014
Acknowledgements

Embarking on the journey of pursuing graduate studies has been an eye opening experience that has taught me a lot about the field of Environmental Engineering and exposed me to the challenges of the research arena. A big part of this journey is embodied in this report. I would like to take this opportunity to express my gratitude to everyone who has supported me throughout my MSc. thesis project.

First of all, I would like to thank Dr. Emad Imam who has guided me throughout this study with close observation, constructive discussions and valuable knowledge. I express my warmest gratitude towards him for introducing me to the field of optimization and for pushing me beyond my limits to learn new things and be patient.

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Dr. Edward Smith and the AUC Environmental Program faculty have played a major role in educating me with the basics and equipping me with the technical background in the field that I am most passionate about and I am very thankful for their effort.

Finally, I am filled with gratitude towards my family and friends for their relentless support and cheerleading. Most importantly I would like to thank my parents who have always been my role models and for believing in me no matter what.
Abstract

Biosludge is a solid waste byproduct of wastewater treatment. The biosludge treatment and management system represents an independent treatment stream in a wastewater treatment plant (WWTP). The system includes several treatment units that may occupy a large part of the wastewater treatment plant and significantly adds to its capital and running cost. The re-use of the processed biosludge or its disposal affects how it is treated and managed. The optimum management system of biosludge varies according to the type of wastewater generating the biosludge, applicable environmental legislations as well as site and climate conditions. Designing an optimum management system for biosludge generated from plants treating wastewater of Gas-To-Liquid (GTL) plants is important in many areas, such as the Gulf area. In cases where the GTL plant is located in an area that has high land cost, warm arid climate and a lack of sludge re-use markets, a biosludge management system that is optimized for such conditions is needed. Literature on the optimization of biosludge management systems is rather limited, although design codes exist that deal with conventional sludge management systems generated from municipal wastewater treatment plants.

This research consists of two parts: (i) experimental investigation of the characteristics of GTL biosludge and its aerobic treatability, and (ii) developing a design model to obtain the optimum design of biosludge management systems in general, and the GTL biosludge in particular. Biosludge generated from an existing GTL WWTP was investigated. Sludge samples were collected and analyzed for solid content. Lab results characterized the biosludge to have an organic content of more than 80% of its dry solids content qualifying digestion as an adequate volume reduction and stabilization technique. Aerobic digestion achieved solid content reduction values of as high as 70% in 9 weeks. Results indicate that the decay constant specific to the investigated GTL biosludge is 0.0145day$^{-1}$.

The design model consists of three sub-models: a sizing and design sub-model, a simulation sub-model, and a cost and optimization sub-model. The recommended treatment units for the GTL biosludge are Aerobic Digestion (AD), Dewatering by Centrifuge, and Drying Beds (DB). The design sub-model is used to size the AD, centrifuge and DB for selected values of residence times in the AD and DB. The simulation sub-model is then used to track the daily changes of the water and solids content of the inflow biosludge through the AD, centrifuge and DB accounting for the ambient temperature that varies on a daily basis throughout the whole year. The simulation-sub-model predicts the daily final sludge amounts collected from the DB and transported to the landfill (LF) for disposal. The cost and optimization sub-model generates the alternative designs that are sized by the design sub-model and calculates the capital and operating costs based on the results of the simulation sub-model for each design alternative. Two main design variables are varied to identify the optimum design: residence time in the AD and time spent in the DB. The minimum cost alternative is chosen as the optimal treatment line-up recommendation. The minimum
cost is a trade-off between the cost of biosludge being aerated for a longer time and the drying and disposal cost savings achieved by smaller volumes of produced biosludge.

The model was applied to obtain the optimum management system for a daily feed of 360 tons of GTL biosludge under five cases: (i) minimum cost, (ii) with constraint on the daily disposal amount of 20 tons, (iii) potential re-use of processed sludge, (iv) domestic biosludge, and (v) refinery biosludge applications. The optimum design for case (i) did not include the AD as its cost was higher than the reduction in cost of the subsequent treatment units. The design comprised of the centrifuge, drying beds (for 8 days), transportation and disposal to LF. This alternative results in 20.3 tons/day at a unit cost of $7.26/ton. The design for case (ii) ensured a rate of disposed sludge of less than 20 tons to meet the EPA requirement hence required an AD with a residence time of 21 days plus 8 days in the DB with a unit cost of $9.97/ton. Case (iii) suggested a solution for GTL biosludge to qualify for the land application requirement based on 28 days of residence time in the aerobic digester and one day in the drying beds. This would result in 16.9 tons/day at unit cost of $10.69/ton. Cases (iv) and (v) deal with domestic and refinery biosludges that have higher decay constants resulting in a drop in amounts and costs of biosludge produced to 16.8 tons/d of sewage sludge costing $6.01/ton and 10.21 tons/d of refinery sludge costing $4.55/ton. The model gives results on an average of one year but allows the versatility of monitoring seasonal performances and varying the design accordingly.
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<td>AHP</td>
<td>Analytic Hierarchy Process</td>
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<td>APHA</td>
<td>American Public Health Association</td>
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<td>ASTM</td>
<td>American Society for Testing and Materials</td>
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<td>BOD₅</td>
<td>Biological Oxygen Demand</td>
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<td>CAPEX</td>
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<td>COD</td>
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<td>CRF</td>
<td>Cost Recovery Factor</td>
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<td>DB</td>
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<td>DO</td>
<td>Dissolved Oxygen</td>
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<td>DSS</td>
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<td>SCFM</td>
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Chapter 1: Introduction
Biosludge is the major solid waste produced from municipal and industrial Wastewater Treatment Plants (WWTP) alike. Biosludge is typically produced in considerable volumes that are either reused or disposed of safely. The biosludge treatment train is an independent section of any WWTP that may take a considerable percentage of the plant and represent a large portion of its capital and running costs. Hence, the biosludge treatment line-up in a WWTP is an important aspect of the plant design and operation, needed to achieve the required environmental standards at minimal costs while taking into consideration other site-specific constraints.

1.1. Objective

This study focuses on the development of a biosludge handling optimization model using biosludge produced from a Gas-To-Liquid (GTL) WWTP. Several factors affect the choice of an optimal biosludge treatment system including whether the treated biosludge will be disposed of or reused, the composition of the biosludge and its responsiveness to different treatment techniques, the availability and cost of land, environmental conditions, legislative requirements as well as cost drivers. Designing an optimum biosludge management system for GTL biosludge is useful in many cases especially in the Gulf area. For a case where land costs are above average, climatic conditions are warm and arid and there is a lack of treated biosludge reuse markets, an optimum biosludge management system must be suggested as a tailored solution for such a case.

1.2. Statement of the Problem

Biosludge treatment demands a considerable percentage of any WWTP’s capital and running costs. It is also imperative to treat the produced biosludge to achieve volume reduction and stabilization to be suitable for safe disposal or reuse in accordance with environmental legislation. Furthermore, due to the broad variance in biosludge qualities resulting from different industries, different treatment line-up combinations are rendered optimal to achieve the required qualities and quantities for each application. Moreover, there is no standard solution to treat biosludge hence; engineers follow certain technical design codes to decide on the suitable treatment units to treat the biosludge at hand. Relying on design codes results in a line-up that disregards the effect of external factors like for example cost and availability of land, variations in ambient temperature from one season to another and other site-specific conditions. Design codes are resorted to due to a lack of models that assist the designer to decide on the optimal line-up for the treatment of a certain biosludge composition.

This study uses biosludge produced from a GTL WWTP as an application that embodies the suggested problem. The plant is located in a rising country with high land costs, high temperatures and a lack of biosludge reuse opportunities. Deciding on the best treatment line-up and the sizing of each treatment unit, taking into consideration cost minimization and environmental constraints, was not a
straightforward task. Research and lab tests proved that digestion, dewatering and drying are the optimal treatment stages to achieve the required biosludge volumes and quality for safe disposal. The model needed to factor in such variations and reflect their effect on performance and cost while considering environmental fluctuations over one year as well as rate the suitability of the biosludge for reuse or disposal. A model was needed to thoroughly design the suggested treatment line-up as well as have the versatility of being applied to other biosludge types in order to address the issue of lack of standard optimization models in the field of biosludge management.

1.3. Motivation

As environmental awareness spreads across industries and cultures, environmental regulations have constrained how WWTPs deal with biosludge waste. Such regulations require the proper design and installation of a functional and feasible biosludge treatment plant as an imperative part of any WWTPs as well as taking into consideration environmental and operational constraints.

Biosludge generated from plants treating wastewater from GTL plants is not well studied nor thoroughly characterized. Its feasible treatment by digestion techniques, both aerobic and anaerobic is not fully investigated. To derive an optimal treatment and management system for this GTL biosludge, a study is needed for its characterization and to find the most suited methods of treatment and handling.

Literature about optimizing biosludge management systems in general is limited and almost non-existing for GTL biosludge in particular. However, a couple of optimization studies were carried out.

Tang et al realized a model to prioritize sludge and wastewater treatment alternatives to select the optimum process for any given situation [1]. The model was particularly developed for developing countries where the trade-off between cost and effectiveness needs to be addressed while taking into consideration socio-cultural and environmental conditions [1]. Linear programming models have been developed to optimize the design of sludge treatment processes at the lowest cost but were soon found to be inadequate for optimization of these processes as they have a more dynamic nature [1]. An Analytic Hierarchy Process (AHP) was selected because of its ability to take into account environmental and social aspects [1]. Parameters considered included land size, location and cost, economic factors, climatic conditions, sludge nature and age, local construction skills, community support and other technical factors [1]. However, the AHP is not quantitative in a way that would apply to obtaining the optimum design of the sludge management system.

Bertanza et al emphasized the importance of optimizing the dewatering stage in the biosludge management system [2]. They carried out an experimental methodology to evaluate the technical and financial performance of dewatering devices that can be used as a Decision Support System (DSS) for WWTP managers [2]. The limitation of this study lies in its focus on only one treatment stage however; this choice was made
due to the high volume reduction potential achieved through dewatering coupled with sludge’s poor dewatering qualities.

It appears that there is a great need to develop an optimization design for biosludge management systems in general and for GTL biosludge in particular. The model should take into consideration technical aspects of treatment units, environmental conditions as well as climatic and land availability considerations.

1.4. General Approach

The following section summarizes the tasks planned to achieve the objectives of this research. The tasks are divided into two main stages: (i) experimental investigation of GTL biosludge, and (ii) optimization model development.

Biosludge generated from an existing GTL wastewater treatment plant is to be investigated. Sludge samples are collected and analyzed for solid content. Lab analyses should characterize the GTL biosludge through measuring the organic content percentage of its dry solids content. Experiments should also quantify the solid reduction achieved by aerobic digestion over time through simulating plant activity using lab scale reactors. Results should indicate the decay constant specific to the investigated GTL biosludge.

The optimization model should allow the designer to make the best-informed decision by weighing out different factors according to project conditions. The designer needs to make a series of decisions relating to the performance and cost of each treatment unit. The model simulates three stages to treat biosludge; Aerobic Digester (AD), centrifuge unit and Drying Beds (DB). The model is then run through varying two variables alternatively, allowing the designer to retrieve a set of technically feasible alternatives where the minimum cost option is suggested as the optimal line-up. The model utilizes a real life case as a basis for its design where the properties of GTL biosludge are input in the model allowing for the design of each treatment unit. The units are sized taking into consideration environmental conditions such as temperature, design codes, space availability and WWTP effluent specifications. However, the minimum cost alternative might not always be the recommended option as compliance with environmental legislations might dictate the need to use another alternative. Finally, the model is expected to provide the designer with the amount of biosludge ultimately produced from the treatment line-up and its associated costs averaged over one year. The model is also expected to have the versatility to generate results for other biosludge types including sewage sludge.

Consequently, the developed design model consists of three sub-models: a sizing and design sub-model, a simulation sub-model, and cost and optimization sub-model.

The design sub-model is used to size the AD, centrifuge, and DB for selected values of residence times in the AD and DB. The simulation sub-model is then used to track the daily changes of the water and solids content of the inflow biosludge through the
AD, centrifuge and DB accounting for the ambient temperature that varies on a daily basis throughout the year. The mass flux of biosludge with known water to solid content ratio is fed through the line-up. The Aerobic Digester (AD) then reduces the solids content by digesting the organic fraction of its makeup. Biosludge is then discharged from the AD in the same amounts but with higher water content where it is fed into the centrifuge, which is expected to dewater it to reach a preset water content percentage. Finally, the biosludge is sent off to drying beds to dry and lose further water content through drainage and evaporation. Biosludge is then either disposed in landfills or reused in land application. The simulation sub-model predicts the daily amounts of final sludge collected from the DB and transported to the landfill (LF) for disposal. The cost and optimization sub-model generates the alternative designs sized by the design sub-model and calculates the capital and operating costs based on the results of the simulation sub-model for each design alternative. The minimum cost alternative is chosen as the optimal treatment line-up recommendation. The minimum cost is a trade-off between the cost of biosludge being aerated for a longer time and the drying and disposal cost savings achieved by smaller volumes of produced biosludge.

The model is then applied to obtain the optimum management system for a 360 ton per day of GTL biosludge under five cases: (i) minimum cost, (ii) with constraint on the daily disposal rate of 20 ton, (iii) potential re-use of processed sludge, (iv) domestic biosludge, and (v) refinery biosludge applications.

The report is organized as follows; section 2 gives the background and the literature review where GTL WWTPs are discussed briefly, the characteristics and management of GTL biosludge are detailed and finally previous work on biosludge treatment models is presented. Section 3 gives an overview of the simulation sub-model of the optimization model where the effect of each treatment unit of biosludge quantity and composition is simulated. Section 4 illustrates the lab experiments run on GTL biosludge and the results retrieved to run the model. Section 5 discusses the design sub-model and optimization and cost sub-models which assess the different alternatives. Section 6 utilizes the model to run five chosen applications to test its applicability to different scenarios. Finally, section 7 concludes the work and proposes recommendations.
Chapter 2: Background and Review of Literature
This section includes a background on the handling and treatment of biosludge with a focus on Gas-To-Liquid (GTL) biosludge. Furthermore, previous work on the management of biosludge and optimization studies is discussed.

2.1. General

Biosludge is defined as the “precipitated solid matter produced by water and sewage treatment processes” [3]. It is the end product of biological, physical or chemical wastewater treatment [4]. Sludge is comprised of a microbial consortium as well as organic and inorganic matter held together in a matrix formed by exocellular biopolymer and cations [5]. Biosludge water content varies between 95% and 99%. Biosludge is produced from sewage treatment and industrial wastewater treatment plants (WWTPs) hence, biosludge composition varies widely depending on the application. Such variation in biosludge characterizations dictates different treatment processes suited for each application.

Biosludge is either treated for reuse or safe disposal in compliance with certain environmental standards. The optimal treatment line-up is chosen for each biosludge type to include volume reduction and stabilization stages. The U.S. Environmental Protection Agency (EPA) has proposed certain techniques to achieve volume reduction and stabilization known as Processes to Significantly Reduce Pathogens (PSRPs) [6]. Such processes include aerobic digestion where biosludge is agitated with oxygen for a certain residence time at a certain temperature to achieve stabilization of the organic content [6]. Other methods include air-drying where the biosludge is left to dry on sand beds or paved basins and lime stabilization, which is where sufficient lime is added to the biosludge to raise its pH [6]. As for composting, windrows or static vessels are used to aerate biosludge at high temperatures to produce compost [6]. Anaerobic digestion is another digestion technique where biosludge is treated in the absence of air at high temperatures for a certain residence time to produce stabilized biosludge and biogas [6]. The optimal treatment technique is chosen according to the characteristics of the biosludge that vary according to the application. Techniques might be applied in combination to one another to achieve the required quality and volumes. Once sludge is left to separate, it is mostly highly putrescible organic matter hence; a stabilization treatment technique is inevitable to allow for inert biosludge fit for reuse or disposal [7]. Furthermore, given the high water content in biosludge, other volume reduction stages include dewatering using mechanical equipment like centrifuge units as well as natural water loss stages like drying beds, which are both added after digestion stages [7].

For the purpose of this study, the focus will be on biosludge produced from industrial wastewater treatment specifically from GTL plants.
2.2. Treatment of Wastewater from GTL Plants

A GTL plant primarily produces hydrocarbon products however; other by-products are naturally produced including wastewater, biosludge, salt and sulphur. Wastewater can be reused after treatment where it is recycled for use in plant utilities or for irrigation purposes. Biosludge is produced during treatment of effluent water in the WWTP. This section gives an overview on GTL plants and their WWTPs where biosludge is produced.

2.2.1. Overview of GTL Plants

The GTL process starts with producing natural gas from offshore or onshore fields. Water and condensates are then separated from the gas as well as other components such as sulphur, which are removed and cleaned [8]. Gas then goes through the cooling stage where natural gas liquids are removed via distillation and the remaining pure natural gas flow to the gasification unit [8]. The next stage involves producing synthesis gas in the gasifier at around 1500°C where methane and oxygen are converted into a mixture of hydrogen and carbon monoxide constituting the synthesis gas which is also referred to as syngas [8]. The syngas then enters a designated reactor to be converted into long-chained waxy hydrocarbons and water [8]. GTL plants create a range of products from natural gas, where the long hydrocarbon molecules from the GTL reactor are contacted with hydrogen and cracked into a range of smaller molecules of different length and shape [8]. Distillation then separates out the products at different boiling points [8]. Figure 1 further illustrates a high level representation of the GTL process. GTL products include GTL naphtha, which is used for plastic manufacturing, GTL kerosene, which is used as a jet fuel or as a home heating fuel, GTL normal paraffins used for detergents as well as being used in gasoil and base oils [8].

For the purpose of this research it is imperative to focus on the units that feed wastewater into the WWTP stream. The processes occurring within the separation stage and the reactor that produces the syngas result in considerable amounts of wastewater [8]. Side reactions within the processes produce formic acid, acetic acid,
propionic acid, methanol, ethanol, propanol and aldehydes, which contaminate the wastewater stream [10].

Wastewater from the GTL process is not the only stream feeding into a typical GTL WWTP. Other wastewater streams from across the GTL plant are directed to the WWTP including, accidently oil contaminated water as well as potentially oil contaminated condensate [10]. All wastewater streams gather in corrugated plate interceptors (CPIs) before pouring into the Effluent Treatment Plant’s (ETP) buffer tank. Wastewater then flows into the Flocculation Flotation Unit (FFU) from which the biosludge of interest is produced as a by-product however; the wastewater passes on to the biotreater then to the Submerged Ultra Filtration Unit (SUF) for further processing. Excess sludge is produced from both stages to be recycled back to the FFU, which ultimately feeds into the Sludge Holding Tank (SHT) [10].

Tracing the GTL process line-up leading to the WWTP where biosludge is produced, gives an idea of the possible biosludge constituents. GTL wastewater is contaminated with aromatic discharges, hydrocarbons, suspended solids, soot and sulphides as well as HCl, FeCl₃, NaOH, cation coagulant and anion flocculant [10].

2.2.2. Treatment Processes of GTL WWTP

The WWTP line up for GTL biosludge is depicted in figure 2. GTL effluent feeds into a Water Distillation Unit (WDU) and then flows to the Buffer Tank followed by the FFU where chemicals are added to the wastewater and agitated at an appropriate rate to produce wastewater to be fed into the aeration tank and biosludge that is fed into the SHT [10]. The SHT is not inoculated with bacteria as it was originally designed as a holding tank. Wastewater is then directed from the aeration tank to the clarifier and finally to the tertiary treatment stage that includes Ultra-Filtration and Reverse Osmosis (RO) [10].
2.2.3. Sources and Characteristics of Biosludge

Biosludge fed into the SHT is sourced mainly from the FFU. Wastewater flows into the FFU from the buffer tank and the off-spec tank as well as from the recycled stream of the clarifier. For the purpose of this research, biosludge samples were collected prior to entering the SHT as indicated by the red point in figure 2.

Biosludge characteristics vary widely due to the wide spectrum of biosludge producing industries. Hence the optimal treatment train is chosen on a per case basis. Solid reduction techniques are a major decision factor as they affect the amount and quality of waste ultimately disposed or reused. High organic content biosludge samples are best treated through digestion techniques. Biodegradable biological solids content cannot be tested for directly hence, the Volatile Suspended Solids (VSS) concentration is conventionally used to determine the organic content [11]. The higher the organic content, the more effective digestion is at minimizing the solid content of biosludge and in turn stabilization of the final disposed waste and reduction of its total volume. For the case of GTL biosludge, samples were collected from the field and tested for organic content to check the suitability of digestion techniques in treating GTL biosludge. Experimental results are further detailed in a later chapter of this study.

Further characterization of GTL biosludge seeks knowledge of the plant effluent constituents as well as the added chemicals. The final biosludge is expected to contain water, soot, biomass, oil, ferric (III) hydroxide and other suspended solids such as sand, FFU coagulant, flocculating agents and trace metals [12]. Organics in biosludge is mainly composed of dead bacterial matter and a small amount of hydrocarbons. The FFU is typically responsible for removal of solids and oil however; in some cases the FFU also receives a biosludge slurry stream from the biotreater resulting in some raw incoming wastewater to be mixed with the biosludge causing the appearance of oil and solid traces [12]. GTL biosludge is also expected to contain iron hydroxide, which is formed when Iron (III) Chloride (FeCl₃) is dosed into the FFU. In this application, FeCl₃ reacts with the hydroxide ion in water to form iron hydroxide flocs that help remove suspended materials [12]. Furthermore, GTL biosludge is expected to contain some trace elements. These trace elements are present in the GTL effluent as corrosion and erosion products as well as chemicals that are added throughout the process of the GTL plant, including inhibitors, nutrients and flocculating agents [12]. GTL biosludge contains very low concentrations of pathogens since the GTL process does not introduce pathogens into the wastewater and in turn low concentrations are expected in the biosludge. Other Total Suspended Solids (TSS) contributors in the biosludge include fine particulates that enter the biotreater such as dust, sand, corrosion products and precipitated salts [12]. It was important to characterize the quality of GTL biosludge to decide on the optimal treatment train for its handling.
2.3. Management of GTL Biosludge

GTL biosludge is treated primarily through aerobic digestion by being left in an appropriately sized reactor for a recommended residence time. It is then dewatered mechanically when passed by a continuously operating centrifuge unit. Finally the biosludge is transported to a suitable location to be left in designated drying beds where significant volume reduction is achieved. Finally, the biosludge is disposed of in landfill waste cells in compliance with environmental safety standards. In cases where agriculture is prevalent, treated biosludge could be used as a soil conditioner however; it would need further treatment and handling to be suitable for soil application.

2.3.1. Treatment Processes

Processes discussed in this subsection are digestion specifically aerobic digestion; dewatering using the centrifuge as well as the drying beds stage.

Aerobic Digester (AD)

Digestion is a widely used biological process to treat and stabilize biosludge produced from WWTPs [13]. Aerobic digestion is one of the main means to treat biosludge that satisfy vector attraction reduction requirements [14]. Aerobic digestion is the biochemical oxidative stabilization of biosludge in the presence of oxygen [4]. Digestion, as a biosludge treatment technique, results a reduction in VS and odors allowing for safe land application and disposal [13].

Aerobic digestion is a commonly used method for treatment of biosludge. The process takes place in the endogenous respiration phase where the supply of available substrate is depleted causing microorganisms to resort to consuming their own protoplasm to obtain energy for cell maintenance reactions thus achieving endogenous oxidation of cell tissue. This leads to stabilization of biosludge as well as a substantial reduction in its volume. However, some of the cell material, utilized at a negligible rate, is non-biodegradable [11]. The process is initiated by a culture of aerobic microorganisms that feed on organic matter in an optimal environment causing its degradation. The bacteria either initially exists within the biosludge matrix or is inoculated prior to reactor operation. The consumed organic material is utilized to produce new microorganisms, causing an increase in biomass. The residue is oxidized into water, carbon dioxide and soluble stable material that provide energy for maintenance of microorganisms’ activities. This cycle continues until the organic material is exhausted causing the microorganisms to exercise endogenous respiration where the cellular material is oxidized to provide the energy requirements needed for life support. If this condition is maintained for a considerable amount of time, the quantity of biomass will be significantly reduced causing the sludge to reach a low energy state adequate to qualify for reuse or disposal in the environment [14]. As the
process ventures into the endogenous phase, cell tissue is aerobically oxidized to CO$_2$, H$_2$O, NH$^+$, NO$^-$, and NO$^{-3}$ [15].

\[
\text{organic matter} + O_2 \xrightarrow{\text{bacteria}} \text{cellular material} + \text{stabilized organic matter} + CO_2 + H_2O \quad (1)
\]

\[
\text{cellular material} + O_2 \xrightarrow{\text{bacteria}} \text{digested sludge} + CO_2 + H_2O \quad (2)
\]

Equations 1 and 2 illustrate the aerobic digestion processes. Equation 1 shows the oxidation of organic matter to produce new biomass. This cellular material is then oxidized to produce digested sludge. Equation 2 quantifies the endogenous respiration phase, which is the main reaction in aerobic digestion [14].

Benefits of aerobic digestion include its ability to stabilize sludge with regards to volatile content and biological activity as it reduces VSS to 40-50% of its initial concentration. Its capital cost is much less than anaerobic digestion for plants with capacities of less than 19,000 m$^3$/d [7]. Furthermore, aerobic reactors are relatively easy to operate and the produced supernatant is low in BOD$_5$ and ammonia nitrogen hence, it does not generate nuisance odors. Under thermophilic conditions, anaerobic digestion is thought to achieve 100% pathogen destruction [7]. However, produced sludge usually has poor mechanical dewatering characteristics and the process does not remove any heavy metals. Furthermore, continuously supplying oxygen is not cost effective and the process performance lacks versatility being considerably sensitive to changes in temperature, location and tank material [15].

Aerobic digestion can be set up in a number of different design configurations. The treatment line-up used for GTL biosludge treatment is the conventional semi-batch operation set-up that is clearly illustrated in figure 3. Solids are passed directly from the thickeners into the aerobic digesters. However for smaller scale plants, a thickener is not needed after the aerobic digestion stage. The time needed to fill the digester is directly proportional to the tank volume, biosludge volume and precipitation as well as evaporation rates. An implementation of the batch set-up takes place during the filling operation where the biosludge undergoes continuous aeration in less than 2 to 3 weeks. Aeration is then discontinued and thickened solids are removed until a sufficient amount of stabilized solid is removed then the cycle is repeated. Between cycles, some stabilized biosludge is left in the aerator to ensure the sufficient microbial population needed for degradation in the following cycle [15].
Other design configurations include, conventional continuous operation, which is similar to the semi-batch process, as solids are pumped directly from the thickener into the aerobic digester. The aerator operates at a fixed level, with the overflow going to a solids-liquid separator. Thickened and stabilized solids are either recycled back to the digestion tank or removed for further processing [15]. Untreated biosludge is fed into the digester, thickened from solids at the same rate on a daily basis [6]. Continuous operation is not preferred since a separate sedimentation-tank needs to be added for larger plants to allow for continuous flow [15].

Design configurations also take into consideration surrounding environmental factors where if ambient temperatures are not within the thermophilic range (greater than 45°C), it is recommended to implement an autothermal thermophilic aerobic digestion configuration. Autothermal means that the increase in temperature is due to the exothermic breakdown of organic and cellular material taking place during aerobic digestion. However, digesters must be covered to retain heat. High temperatures minimize the retention time needed to achieve a given degree of solids reduction. Also, such high temperature may lead to almost complete destruction of pathogens [9]. This method needs aeration either by air as a source of oxygen or through a dedicated oxygen source. For the GTL plant studied in this research, the ambient temperatures are sufficient to achieve acceptable solids reduction rates hence; the aforementioned configuration would not be needed.

The design of a functional aerobic digestion system requires taking a few design parameters into consideration. Sludge Loading Rate (SLR) is defined as the mass of solids being fed into the reactor per unit volume per unit time. Its units for this case are Kg.VSS/m^3/d as shown in equation 3 [15]. Typical values for this parameter allow for the proper choice of flow rate and tank volume however, for the purpose of this study, the flow rate is fixed by the effluent rate fed out of the WWTP and hence, the other parameters are adjusted accordingly. Below is the formula for SLR.

\[
SLR = \frac{SQ}{V} \frac{kg}{m^3/day}
\]

S = the amount of solids loaded into the reactor, Kg VSS
Q = the flow rate of biosludge into the reactor, m^3/d
V = the reactor volume, m^3

Another important parameter is the Solids Retention Time (SRT), which is the amount of time solids need to spend in a reactor to maintain a healthy food to mass ratio. It is typically measured in days [15]. SRT is derived using equation 4:
\[ V = \frac{Q(X_1 + YS_1)}{X(k_aP_v + \frac{1}{SR_T})} \]  

\[ (4) \]

\( V \) = reactor volume, m\(^3\)
\( S_1 \) = influent BOD
\( Y \) = fraction of influent BOD consisting of raw primary solids
\( P_v \) = volatile fraction of digester suspended solids
\( k_a \) = reaction rate constant
\( X \) = MLSS concentration in the reactor, mg/L
\( Q \) = flow rate of wasted biosludge, m\(^3\)/d

For the purpose of this research, biosludge samples are collected and analyzed at different SRTs to calculate the decay constant’s value.

Solids concentration is a design parameter that ensures that a certain food-to-mass ratio has to be maintained for bacteria to digest biosludge aerobically as shown in equation 5 [15].

\[ \frac{F}{M} = \frac{S \cdot Q}{X \cdot V} \]  

\[ (5) \]

\( S \) = substrate concentration in the reactor, mg/L
\( Q \) = flow rate of biosludge into and out of reactor, m\(^3\)/d
\( X \) = MLSS concentration in the reactor, mg/L
\( V \) = reactor volume, m\(^3\)

Other crucial design parameters include oxygen requirement, mixing rate and chemical dosage. The oxygen requirement requires thorough calculations to achieve the targeted degradation rates. The typical amount of oxygen needed to reduce a pound of Volatile Solids (VS) is around 0.789 to 0.939 kg [15]. On the other hand, monitoring a 2-3mg/L DO concentration is maintained throughout the experiment [6]. Mixing rate is a crucial design consideration as it is imperative to keep solids in suspension and expose the deoxygenated liquid to aeration [15]. It also ensures that substrate is continuously in contact with microorganisms. Mixing rates depend on reactor volume and geometry as well as on the type of aeration equipment used [6]. Aeration could be counted upon for agitation for smaller volume set-ups. Finally chemical dosage needs to be adjusted to ensure that pH and alkalinity are kept in the optimal range. The addition of HCl or NaOH might be necessary to ensure an optimal environment for microorganisms [15].

Centrifuge

Moving onto the dewatering treatment stage, since biosludge typically has over 80% moisture content, dewatering is a crucial treatment stage since it plays a main role in overall volume reduction. The selection of an appropriate sludge dewatering technology depends primarily on biosludge characteristics and on whether the biosludge will be reused or disposed of safely [16]. If there is an opportunity to reuse
biosludge for land application then lightly dewatered sludge may be adequate [16]. However, in more urban areas, where land is unavailable or land use is restricted due to cost constraints, landfilling or incineration is more likely to be resorted to [16]. For these applications, a more intensely dewatered biosludge is desired and could be achieved through techniques such as centrifugation, belt filter press and vacuum filtration. This study focuses on centrifuge as the chosen mechanical dewatering due to its practicality in terms of space occupancy and its automation capacities. There is a trend towards installing small footprint mechanical dewatering units in biosludge treatment line-ups due to the shortage of land availability and its steeply rising costs [17]. Furthermore, labor costs needed for alternative dewatering techniques have pushed the market towards automated options such as centrifuges.

In centrifugation, a solid bowl centrifuge concentrates the solids using a centrifugal force [16]. Biosludge enters the centrifuge after the solid reduction stage. The influent biosludge is typically high in water content in the range of 90-95%. It achieves water-solid separation by settlement and consolidation of solids under the influence of strong centrifugal forces generated in high speed rotating machines [17]. Two streams are produced from the centrifuge, the water stream, known as centrate and the collection of dried solids referred to as cake solids [16]. The centrifuge is capable of handling a certain range of influent solid content and is set to produce a preset dry solids percentage of biosludge cake with varying concentration of influent. The centrate is assumed to be purely water since a negligible amount of solids are lost in the centrate. Temperature variations do not affect the performance of the centrifuge. Typical solid cake concentration produced from centrifuges is 20-25% [17]. Polymer addition is required for most wastewater sludges to ensure optimal operation [16]. The added polymer concentrations vary according to the variations of influent biosludge solid content. Extensive literature was carried out to derive the optimal polymer types for each case.

A centrifuge is essentially a sedimentation device in which solid liquid separation takes place assisted by a centrifugal force [18]. There are different types of centrifuges including the Continuous Solid Bowl Centrifuge, which is made up of a rotating bowl that acts as a settling vessel and a conveyor belt, which discharges settled solids, as shown in figure 4 [18]. The biosludge is fed through a stationary pipe to flow into the rotating bowl causing the slurry to form an annular pool, the height of which is controlled by effluent weirs [18]. The liquid flows over the overflow weirs while the sludge solids move across the beaching incline to the outlet ports.
Another type of centrifuge is the Basket Centrifuge also known as imperforated bowl-knife discharge unit, which is mainly used for smaller operations. Feed is charged through an annular ring as the unit rotates around it [18]. The cake builds within the basket while the centrate builds over a baffle on top of the unit, as shown in figure 5 [18].

The third main type of centrifuge is the Disc Centrifuge where biosludge is distributed between the narrow channels formed by stacked conical discs as shown in figure 6 [18]. Collected sludge is discharged through small orifices in the bowl wall [18].
Usually centrifuges bowls have perforated walls that create a fine mesh filter basket to control the size of particles constituting the biosludge discharge [17].

**Drying Beds**

The drying beds stage is imperative to volume reduction as the majority of water content is lost through drying. The bulk of water lost during the drying beds stage is lost through drainage that occurs once biosludge is spread out on drying beds with minimal thickness. The rest of the water is lost through evaporation hence; drying beds are recommended for areas with high solar radiation [19]. Figure 7 shows the streams of water lost during drying bed operation.

The advantages of using drying beds lies in its low maintenance nature, as they require low energy consumption, low operational skills and low chemical consumption [19]. However, drying beds need considerable amounts of land hence, if the cost of land is an issue, the capital cost of this treatment stage would be a factor worth considering.
Drying beds are either sand beds or paved beds. Sand drying beds are more common at small to moderate sized WWTPs however they need considerable operational maintenance [20]. Paved beds are used as an asphalt or concrete base with tilted slopes to allow for the collection of drainage water, which seeps through the designed pores into the underground perforated pipes as shown in figure 8 [20]. The perforated pipe network collects drained water for treatment or disposal.

Another type of drying beds are vacuum-assisted drying beds which work best with low solid concentration solids as the system is equipped with a vacuum pump to assist with the separation process [21].

Typical drying beds achieve a cake of 40–45% solids content for a residence time of 2–6 weeks in good weather [21]. Chemical conditioning reduces dewatering time by 50% or more [21]. Solids contents as high as 85 to 90% have been achieved on sand beds, but normally, the times required to achieve such dry sludge cakes are impractical or require very high temperature locations [21].

The main aspects which affect the design and performance of drying beds includes sludge condition, sludge characteristics and age, soil permeability and land availability and cost [21].

![Figure 8: Paved Drying Beds Design [20]](image)

### 2.3.2. Disposal and Reuse of Treated Biosludge

Biosludge qualifies as solid waste that needs to be treated for reuse or disposal to evade its harmful presence in the environment and to reuse its organic component. Direct landfill disposal of biosludge used to be the conventional disposal route however; stringent environmental regulations were put in place confining direct landfilling as a plausible disposal option due to its threatening effect on the environment. Furthermore, incineration is another alternative to treat and dispose of sludge however; its application is questionable due to its adverse environmental impact and high cost [13].
Hence, biosludge management developed into a full process to produce environmentally acceptable biosludge quantities and qualities suited for safe disposal or reuse. Disposal into landfills is only an acceptable option provided that the EPA 40 CFR Parts 258 and 257 are met where minimum criteria for all solid waste landfills are set [22]. The types of landfills regulated under Part 257 include those facilities that receive non-hazardous industrial waste such as biosludge [22]. The standard dictates that biosludge is treated to achieve the standards needed for close monitoring and reporting of produced leachate and emissions [23]. Consequently, a treatment process should be put in place to ensure the reduction of volatile organic content and water content. Furthermore, there is an exemption put in place that waives the stringent monitoring standards. The exemption is applicable only to owners or operators of landfill units that receive, on an annual average, less than 20 tons of solid waste per day [24]. Considering the standards and conditions set for biosludge landfilling, a suitable treatment line-up would include digestion, dewatering and drying that allow for volume reduction as well as stabilization.

As for biosludge reuse, a possible option would be selling treated biosludge as soil conditioner [4]. The EPA encourages the use of treated biosludge for land application [6]. However, land application of treated biosludge dictates the compliance with stern regulations put in place due to its threat to human health as raw biosludge hosts pathogenic organisms [6]. Hence, the EPA 40 CFR Part 503 Rule dictates that biosludge must undergo pathogen treatment prior to land application [6]. Human exposure to these pathogens occurs through direct contact as well as through indirect contact such as consumption of pathogen-contaminated crops [6]. In order to comply with EPA requirements, a treatment process should be put in place where biosludge produced from a WWTP is passed through a digestion stage to transform the harmful organic content into a relatively stable or inert organic and inorganic residue such that its quality is rendered suitable for safe disposal or reuse [7]. The biosludge is then dewatered and further dried before it qualifies for land application. The degree of treatment needed for reuse surpasses that needed for landfill disposal.

Depending on client preference and the application, biosludge can be reused for land application in cases where agriculture is prevalent and the revenues achieved from selling soil conditioner out weigh the cost of treatment. As for arid countries, safe disposal in a landfill would be a more cost effective option. Hence, the degree of treatment achieved is a cross match between compliance to regulations, customer preference and cost constraints.
2.4. Previous Work on Biosludge Management

A major part of the literature review is to scope the research arena for previous work done on the matter of interest. This study proposes an optimization model to find the best possible treatment line-up to achieve the smallest volume of stabilized biosludge with minimal cost. Hence, it is useful to look at the optimization studies carried out previously on optimization of biosludge management. The case of GTL biosludge is used as a basis for the model where lab results are used to find the designated decay constant and hence, it would also be useful to have a survey of decay constants of biosludges from different industries, as carried out in the following section.

2.4.1. Biosludge Treatment Survey

One of the major objectives of this research is identifying the decay constant through lab experiments. Hence it was important to research the range of values of biosludge decay constants resulting from other wastewater types to put the findings in perspective.

Biosludge characteristics vary according to the type of wastewater it is produced from for example, sewage biosludge will differ from industrial biosludge. Furthermore industrial biosludge differs from one industry to the other. Nevertheless, not all sewage biosludges possess the same characteristics. One of the properties that differentiates biosludge types and signify digestion effectiveness is the biosludge decay constant ($k_d$).

In the case of completely mixed reactors, biokinetic coefficients including $k_d$ are determined by collecting data from lab-scale or pilot-scale experimental setups operated at various Hydraulic Retention Times (HRTs) and/or at various SRTs [25].

The data collected is focused on the concentration of the degradable biomass present, expressed as degradable Volatile Suspended Solids (VSS) as well as the Chemical Oxygen Demand (COD) concentration of biosludge samples since the rate of destruction of activated biosludge during its endogenous respiration phase is used to derive the $k_d$. The $k_d$ is found to depend on a few factors besides the type of wastewater on which the biosludge is grown including biosludge concentration, biosludge age and on environmental factors such as pH as well as digestion temperature [11].

To gain perspective on how the $k_d$ values derived for the GTL biosludge relate to other biosludge decay capabilities, a survey of $k_d$ values from different wastewater sources was carried out as listed in Table 1 below. The higher the value of $k_d$, the faster the decay rate indicating a higher organic constant which is evident by the high value of decay constants for shrimp processing, dairy products and most municipal waste plants tested for this study. While on the other hand, industrial, tannery and textile biosludge samples yielded considerably lower decay constant values indicating lower organic content or possibly due to the presence of chrome or chlorine.
<table>
<thead>
<tr>
<th>Biosludge Source</th>
<th>$k_d$ (/day)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Municipal (area 1)</td>
<td>0.0189-0.026</td>
<td>[25]</td>
</tr>
<tr>
<td>Domestic (area 1)</td>
<td>0.016-0.07</td>
<td></td>
</tr>
<tr>
<td>Glucose</td>
<td>0.025-0.48</td>
<td></td>
</tr>
<tr>
<td>Synthetic (experiment 1)</td>
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<td></td>
</tr>
<tr>
<td>Municipal (area 2)</td>
<td>0.05-0.16</td>
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<tr>
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<tr>
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<tr>
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<td>Municipal (area 5)</td>
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<tr>
<td>Synthetic (experiment 3)</td>
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<td>[26]</td>
</tr>
<tr>
<td>Activated biosludge</td>
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</tr>
<tr>
<td>Refinery</td>
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<td>Industrial</td>
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<td>Dairy</td>
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<tr>
<td>Pulp &amp; Paper Mill</td>
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<td>[28]</td>
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<td>Shrimp Processing</td>
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<td>Tannery</td>
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<td>[29]</td>
</tr>
<tr>
<td>Textile</td>
<td>0.014</td>
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</table>
2.4.2. Optimization of Biosludge Management Systems

Biosludge management systems are typically designed based on engineering design codes and taking into consideration worst-case scenarios. There are no evident works attempting the design of a comprehensive optimization study analyzing the whole treatment line-up in terms of design variables, objective functions, environmental constraints and cost considerations. However, a couple of studies that touch upon such efforts are discussed in this subsection.

One study carried out by S.L. Tang et al realized the need to develop means of rationally prioritizing sludge and wastewater treatment alternatives to select the optimum process for any given situation [1]. The model was particularly developed for developing countries where the trade-off between cost and effectiveness needs to be addressed while taking into consideration socio-cultural and environmental conditions [1]. Twenty-two parameters were identified for sludge treatment alternatives resulting in ninety-four treatment alternatives as decision variables for the selection of the optimal treatment line-up [1]. Linear programming models have been developed to optimize the design of sludge treatment processes at the lowest cost but were soon found to be inadequate for optimization of these processes as they have a more dynamic nature [1]. The contribution of this model is that it takes into consideration socio-cultural, environmental as well as climatic and land availability considerations [1]. An Analytic Hierarchy Process (AHP) was chosen as the preferred technique for this model owed to its ability to take into account environmental and social aspects [1]. The AHP is based on a mathematical technique where each alternative is given a certain weight and a matrix is developed that allows for the creation of a hierarchy [1]. The hierarchy model is divided into three stages where alternatives are chosen to satisfy objectives that are of priority to the designer [1]. Parameters include land size, location and cost, economic factors, climatic conditions, sludge nature and age, local construction skills, community support and other technical factors [1]. Decision variables were divided into categories that the user can choose from, given that reuse and safe disposal options are offered [1]. The model was applied to a sewage treatment plant in Hong Kong where the best alternative was found to be thickening, mechanical dewatering and incineration for the disposal category and anaerobic digestion and marine disposal for the reuse category [1]. This study provided a good conceptual basis for the development of this research.

Another study carried out by Giorgio Bertanza et al realizes the importance of biosludge management in WWTPs through focusing on the optimization of the dewatering stage [2]. An original experimental methodology to evaluate the technical and financial performance of dewatering devices is used as a Decision Support System (DSS) for WWTP managers [2]. The tool was then applied to two real case studies for reference where the best solution was identified based on economic and site-specific technical evaluations [2]. The choice of chemicals added was another
major decision to be incorporated in the DSS model [2]. This study added a real dimension to the input data used for model development where an experimental phase was carried out [2]. The experiments were run on full-scale machines using live samples for set durations and predefined iterations [2]. Data processing focused on calculating process parameters and checking their consistency, determining technical performance of the system and calculating technical costs [2]. Three different centrifuges were used where the feed and effluent samples were tested for crucial parameters including total dry and volatile solids, COD, flow rate, power consumption, conditioner consumption and other machine specific parameters [2]. Results compared the performance of the three centrifuges with respect to the parameters of concern allowing the user to pinpoint the solution that best fits the plant’s requirement and priorities [2]. The limitation of this study lies in its focus on only one treatment stage however, this choice was made due to the high volume reduction potential achieved through dewatering coupled with sludge’s poor dewatering qualities making it an area of focus. Nevertheless, the techniques used in this study provided a good basis for this research especially on the experimental front.
Chapter 3: Simulation of Biosludge Management System
This research is focused on developing an optimization model to simulate the process of biosludge treatment in order to suggest the best possible treatment line-up. To design a treatment line-up, the engineer needs to make a series of decisions to set certain variables, take into consideration design constraints and evaluate the effect of these decisions on the performance and cost of the system. Evaluation of such decisions is quantified by objective functions, which are functions of design variables that set criteria to single out the best possible design. Objective functions are typically a trade-off between performance and cost.

The model aims at simulating a biosludge management system through tracking the changes in water content and the various types of solids present in the biosludge as it flows from one treatment unit to the other. The sludge flow rates and composition and their treatment will be simulated on a daily basis over a typical year to account for the effect of changes in the sludge and the variable climate since simulating the effects of external variations are expected to affect performance and costs. Also, running the model over one year allows the designer to monitor the variations in performance and cost and vary the design accordingly, which allows flexibility in design choices that result in the optimal system design.

Practice and literature review suggest that the optimal treatment line-up for biosludge in general and GTL in particular with small capacity includes an aerobic digester (AD), followed by a centrifuge and drying beds. The final sludge volumes resulting from the drying beds are either disposed of in landfills, or reused in land application, either directly or after further processing. Hence, the model is broken down into modules; each module is constituted of a set of variables, pre-assigned parameters, design constraints and objective functions.

3.1. Aerobic Digester

The Aerobic Digester (AD) stage is responsible for the reduction in solid content. Figure 9 simulates the operation of the AD. Biosludge fed into the digester is basically made up of a solid component and water content. Biosludge water content is typically in the range of 95-99%.

![Aerobic Digester Tank](image)

**Figure 9: Flow and Mass Diagram of the AD**
Solids reduction is achieved by aerating and agitating a certain volume of biosludge for a certain period of time, known as the residence time (t). Equation 6 shows how the residence time is calculated as a factor the tank volume and influent flow rate.

\[
\text{Residence Time } t (d) = \frac{\text{Volume } V (m^3)}{\text{Flow rate } Q (m^3/d)}
\]  

(6)

The residence time affects the performance of the AD in the sense that the longer the sludge is aerated in the reactor, the higher the drop in the Dry Solids (DS) content of the biosludge due to digestion of the organic matter content of the DS. The degree of drop in DS content achieved per unit time is dependent on the decay constant \(k_d\) day\(^{-1}\), which varies from one sludge type to another. The relation is illustrated in equation 7 where \(X_t\) is the concentration of Total Solids (TS) at residence time (t) in mg/L and \(X_o\) is the initial concentration of TS at time (t=0) in mg/L [30].

\[
X_t = X_o e^{-k_d(T)t}
\]

(7)

For the purpose of this simulation, \(X_o\) is \(S_1\) and \(X_t\) is \(S_2\), as illustrated in figure 9. The percentage drop in solids (D) is derived as in equation 8.

\[
D (%) = \frac{S_2 - S_1}{S_1} \times 100
\]

(8)

where \(S_2 = S_1 e^{-k_d(T)t}\)

Since the model is run over one year, temperature varies on a daily basis hence; the \(k_d\) value needs to be readjusted to reflect the effect of variations in temperature on the performance of the AD in reducing percentage of dry solids. As the temperature increases, the rate of drop in solids increases. To find the \(k_d\) value that matches a certain temperature, equation 9 is used where a value of 1.04 is used for \(\theta\) as a typical value for biosludge in the mesophilic range [6] [31]. The \(k_d(20^\circ C)\) is the given decay constant at 20\(^\circ\)C and the \(k_d(T)\) can be found for any given temperature.

\[
k_d(T) = k_d(20^\circ C) \theta^{(T-20)}
\]

(9)

As shown in figure 9, the AD has no effect on the biosludge volumes produced; it only has effect on its solid concentrations. The AD configuration used for this model is basically an aerated tank, which assumes a constant inflow of biosludge \((Q_1)\) that is equal to the effluent rate. The volume \((V)\) of the tank is designed in accordance with the chosen residence time as shown in equation 6. The AD tank contents are completely mixed and the discharge is taken from the middle of the tank’s height hence, the effluent solids concentration is representative of the tank contents. The resulting solids concentration is a product of being aerated for a chosen residence time. The influent and effluent flow rates are maintained at a constant \(Q_1\) since
digestion is responsible for reducing the solids content to $S_2$ causing an increase in water content from $W_1$ to $W_2$ which is calculated as in equation 10.

$$W_2 = Q_1 - S_2 \quad (10)$$

Biosludge feed from a WWTP is typically measured by weight as tons/day however, the volumetric flow rate of the influent needs to be known in m$^3$/d to size the volume of the digester. To calculate the volumetric flow rate of biosludge, the specific gravity of the sludge is found using equation 11.

$$\gamma_{biosludge} = \gamma_{water} \cdot X_{water} + \gamma_{DS} \cdot X_{DS} \quad (11)$$

The specific weight for water $\gamma_{water}$ is 1.0 and $X_{water}$ could be used as the percentage of water content, which could be between 95% and 97%. While $X_{DS}$ is the percentage of solids content typically ranging between 3-5%. To find the specific weight for the DS content of the biosludge $\gamma_{DS}$, we need to find the specific weight of the Volatile Solids (VS) content and the Fixed Solids (FS) content of the biosludge as well as their percent composition. Consequently, $\gamma_{DS}$ can be calculated using equation 12.

$$\gamma_{DS} = \gamma_{VS} \cdot X_{VS} + \gamma_{FS} \cdot X_{FS} \quad (12)$$

To find the volumetric flow rate given the weight fed into digester per day, equation 13 is used.

$$\text{Volumetric Flow rate} \left( \frac{m^3}{d} \right) = \frac{\text{Biosludge Mass Flux} \left( \frac{t}{d} \right)}{\gamma_{biosludge}} \quad (13)$$

Given the weight of biosludge inflow to the AD in tons/day, equation 13 is used to find the volumetric flow rate in m$^3$/d, which is an important design parameter in sizing the AD tank.

This model ultimately generates alternatives where each alternative simulates the effect of a different residence time and a different tank volume that yield a different digestion rate and in turn different solids concentration of the AD effluent.
3.2. Dewatering (Centrifuge)

The second stage in the line-up is the centrifuge, which is the mechanical dewatering stage responsible for reduction of water content and in turn reduction in biosludge volumes produced. The centrifuge chosen for this model is the continuous solid bowl centrifuge. The centrifuge unit is chosen with the specification of operating at a specific flow rate, which is equal to the AD effluent flow rate $Q_1$.

![Centrifuge Diagram](image)

**Figure 10: Flow and Mass Balance of the Centrifuge**

Figure 10 depicts the centrifuge operation where the centrifuge receives an inflow of biosludge $Q_1$ to produce two streams, a water stream known as centrate ($W_R$), which is recycled back to the WWTP and a biosludge stream $Q_2$ known as sludge cake. The sludge cake is made-up of water content $W_3$ and solid content $S_2$ which is equal to the influent solids concentration since the centrifuge does not affect the solid content as its only function is dewatering. The centrifuge accepts a range of influent solid concentrations that was chosen to cover the range of solids content concentrations resulting from the AD. It then produces an effluent with a predefined solid content percentage $P_c$ chosen as a specification of the purchased dewatering unit. $P_c$ and $S_2$ are used to calculate $Q_2$ and consequently $W_3$ and $W_R$ are found as shown in equation 14, 15 and 16 below.

\[
Q_2 = \frac{S_2 \times 100}{P_c\%} \quad (14)
\]

\[
W_3 = Q_2 - S_2 \quad (15)
\]

\[
W_R = W_2 - W_3 \quad (16)
\]

The optimal operation of the centrifuge unit requires certain amounts of polymer that vary according to the influent biosludge solids concentration to achieve the set effluent solid content percentage. For aerobically digested biosludge, 10 Kg of
polymer is needed for every ton of DS as illustrated in equation 17 [32]. The model assumes the added polymer is non-toxic and is most suited for GTL biosludge.

\[ \text{Polymer (Kg)} = 10 \times S_2 \text{ (tons)} \]  

(17)

Furthermore, one of the main advantages of the centrifuge is that the back drive system maintains the set cake solids level in spite of changing feed concentration via an integral proportional controller [33]. Thus by occasionally observing the centrate and adjusting the polymer accordingly, the system stays optimized [33]. It can be assumed that the solids fed into the centrifuge come out in the biosludge cake unharmed. This assumption is valid due to the typical high recovery rates reported for centrifuges being as high as 95% [33].

Q₂ produced from the centrifuge is typically rated in volumetric terms (gallons per minute or m³/d) however, it is beneficial to track the weight of biosludge produced by the centrifuge in tons/day. Hence, equation 11 and 13 are used to find the new \( \gamma_{\text{biosludge}} \) and in turn find the weight equivalent of the biosludge effluent.

3.3. Drying Beds

Biosludge is then left in drying beds to dewater further and reduce volumes to the minimum before trucking and disposal in landfills. Paved drying beds with installed leaching systems were seen as the optimal set-up for the model as shown in figure 11. Drying beds receive biosludge with a certain water content Q₃ and a solid content of S₂. Drying beds do not affect the solid content as drying only results in a loss of water content.

\[ Q_2 = W_3 + S_2 \]

\[ Q_3 = W_3 + S_2 \]

Volume reduction achieved in the drying beds is done through the loss of moisture content, which is owed to two processes, water drainage \( (W_s) \) through seepage into the leaching system and water evaporation \( (W_E) \). Drainage is the loss of free water within the sludge by gravity. Around 70% of the moisture content of the biosludge is lost through drainage on the first day as shown in equation 18 [34].

\[ W_s = 0.7 \times W_3 \]  

(18)
The rest of the time spent by the biosludge in the drying beds aims to achieve water loss through evaporation where a batch of biosludge is turned into a new bed on a daily basis to ensure uniform exposure of biosludge to ambient conditions. The number of drying beds (N) is set to be equal to the number of days a batch of biosludge is left to dry. Free water evaporation rates are retrieved for the climate at hand and then a reduction factor of 0.6 needs to be applied to these evaporation rates to account for the evaporation rate from a biosludge surface [20]. Equation 19 shows the volumes of water lost through evaporation.

\[
W_E(m^3) = 0.6 \times \text{free water evaporation rate} \left(\frac{m}{d}\right) \times \text{Area of one bed} \times \text{No. of beds (N)}
\]  

(19)

Equation 20 illustrates the volumes of water lost from drying beds in N days and hence; the biosludge volumes trucked to the disposal site per day (Q₃), which can be found using equation 21.

\[
W_4 = W_3 - (W_S + W_E)
\]

(20)

\[
Q_3 = W_4 + S_2
\]

(21)

The size of one bed depends on design engineering standards and the volume of biosludge in a daily batch, which require that the biosludge be tracked in volumetric units. Furthermore, the water lost through seepage and evaporation is also measured in m³ however, it is important to translate the resultant biosludge volumes to weight equivalents using equations 11 and 13 as tons/day is the unit concerned with trucking the biosludge to the landfill disposal site.

3.4. Simulation Example

To illustrate the simulation concept further, the mass balance flowchart in figure 12 summarizes the simulation of the line-up performance on a typical day. Typical numbers are used where biosludge is produced from the WWTP at a rate of 100 tons per day with 95% water content. The model is simulated for sewage sludge having a \(k_d(20^\circC)\) of 0.05 day\(^{-1}\) operating in 25°C ambient temperature. The feed biosludge is assumed to have a VS composition of on average 80% while the FS is 20% of the total DS content. The specific weight of organic content (VS) of biosludge is typically very near to 1.0 and will be used for the purpose of this study as 1.05 while the specific weight of the FS content of biosludge could be taken as 2.0 [35,1].

It is assumed that the biosludge is left in the AD for 14 days and left in the drying beds stage for a week. The centrifuge unit is set to produce an effluent sludge with 20% DS content. The free water evaporation rate for a typical 25°C day is 4 mm/d. The area of one drying bed is assumed to be 100 m².

Figure 12 depicts the modules simulating the line-up as a whole and how numbers vary from one stage to another. A biosludge feed of 100 tons/d and 95% water content
translates to 95 tons of water and 5 tons of dry solid content. Equation 12 is used to find $\delta_{DS}$ for the given VS/FS compositions and specific weights to be 1.24. Equation 11 would then result in a $\gamma_{biosludge_1}$ of 1.01 hence; $Q_1$ would be equal to 99 m$^3$/d according to equation 13. For a residence time of 14 days, an AD tank volume of 1386 m$^3$ is needed according to equation 6.

A 25°C ambient temperature results in a $k_d$ of 0.061 day$^{-1}$ given a 20°C $k_d$ for sewage sludge calculated using equation 9. This figure is then applied to equation 7 to yield $S_2$ in terms of $S_1$ where $S_2 = S_1 e^{-0.061 \times 14 \text{days}} = 0.426 S_1$ which allows us to find the drop in dry solids D% to be 57.4% as illustrated in equation 8. This means that $S_2$ is 2.13 tons, which is a 57.4% drop from the 5 tons of $S_1$. For a constant $Q_1$ of 100 tons, $W_2$ increases to 97.87 tons from the 95 tons of $W_1$ as calculated by equation 10.

The slight change in composition results in a variation of the $\gamma_{biosludge_2}$ to 1.005 hence; the volumetric flow rate out of the AD into the centrifuge is 99.5 m$^3$/d. A compatible centrifuge is installed to match this flow rate. The centrifuge is set to produce a biosludge cake of 20% DS content with an inflow of 2.13% DS content. The actual DS content of 2.13 tons is fixed by weight at 2.13 tons. Hence, equation 14 is used to calculate the resultant biosludge outflow from the centrifuge to the drying beds ($Q_2$) to be 10.65 tons. Using equations 15 and 16, $W_3$ is 8.5 tons while $W_R$ is 89.4 tons. The centrifuge would require 21.3 kg of polymer for a dry solid weight of 2.13 tons according to equation 17.

Another change in composition results in a revised $\gamma_{biosludge_3}$ to 1.05 due to the increase in DS content from 2% to 20%. Hence a volume of 10.1 m$^3$/d is passed on to the drying beds stage with an 8.5 m$^3$ of water content. In the drying beds stage, 70% of the water content is lost in the first day to seepage resulting in a $W_s$ value of 5.95 m$^3$/d. Equation 19 is used to calculate the water lost through evaporation, which is 1.68 m$^3$ for an evaporation rate of 4 mm/d and a drying bed area of 100 m$^2$ for 7 days. This leaves the resulting biosludge with a water content $W_4$ of 4.23 m$^3$ or 4.23 tons since the specific weight of water is 1.0. Drying beds have no effect on the 2.13 tons of DS content resulting in a $Q_3$ of 6.36 tons where the new DS percent content rises to 33.5%.

The produced biosludge is trucked to the disposal site or reused for land application. The new composition of biosludge results in a $\gamma_{biosludge_4}$ of 1.08 resulting in a volume of 5.9 m$^3$/d, which is an important figure in case waste is disposed in a specified landfill volume to be able to calculate landfill lifetime.

The flow and mass balance of biosludge from unit to another for this example is clearly depicted in figure 12.
This section gave an overview of the simulation of a biosludge treatment line-up however, the model is further developed through unit sizing, cost estimations and objective functions in the subsequent chapters. The model will use GTL biosludge as the basis for design but before moving on to the model, lab experiments were carried out to find the decay constant $k_d$ specific to GTL biosludge to be used as a basis for the design.
Chapter 4: Aerobic Digestion of GTL Biosludge Experimental Work
The optimization model is tested using GTL biosludge samples where the aerobic digestion reaction was simulated in a lab experiment to derive the decay constant specific to the GTL biosludge since it varies according to the nature of the biosludge composition at hand. Samples were collected from the GTL WWTP at a sampling point chosen at the feed of the SHT, on a weekly basis for lab analysis as detailed in the following section. This section illustrates the lab results, which aim to define the specific decay constant \( k_d \) specific of GTL biosludge to feed into the optimization model design.

4.1. Experimental Set-up

The aerobic reactor installed in the plant is set-up in a continuous operation mode where a constant rate biosludge influent is fed to the digester and decanted at the same rate. This digester set-up is fitting for plant operation as this treatment stage is part of a line-up that operates in the same manner and it is also more time and cost efficient. However, the lab set-up used for this experiment is a batch set-up since it is more suitable for lab scale operation. Small batch reactors require less auxiliary equipment such as pumps and their control systems are less elaborate and less costly than those for continuous reactors. Batch systems are also adequate for lab work provided their versatility, which allows for intervals between batch runs that give an opportunity to clean the system thoroughly [36]. However, large batch reactors may sometimes be fitted with highly complex control systems hence, are not suitable for plant operations.

A batch wise operation is similar to small-scale preparatory reactions and hence, it was a fitting choice for this research. Components of a batch reactor are completely mixed where reactions take place once reactants are fed into the tank. Reactor contents are continuously mixed and do not leave the reactor through an effluent stream as shown in figure 13. Such set-up is well suited for liquid-phase reactions [36]. In this case, the reaction of concern is digestion and the biosludge is essentially in liquid phase.

![Batch Reactor Set-up](image13.png)
The used lab scale reactors were equipped with an aerator, a mixer, pH, temperature and DO probes. Figure 14 shows a conceptual drawing of the lab set-up.

The aeration of the biosludge was supplied through a circular polyethylene pressure pipe distributor system of aeration stones located at the bottom of each reactor fed by a small aeration pump. The airflow rate was regulated through valves to ensure a DO level of 2-3 mg/L in the biosludge. The DO in the biosludge was occasionally checked [11].

Nine batch experiments were run over the course of 12 weeks in three phases. Reactor 3 was chosen as it was run for 9 weeks and has exhibited the most credible set of results in reference to literature and performance of the other 8 reactors.

Influent biosludge was characterized at the beginning of the experiment and the final biosludge sample is analyzed after experiment abortion. Samples were extracted from the reactor at predefined SRTs, on a weekly basis, for characterization. A sampling procedure was followed to ensure uniformity.

The tested parameters were chosen to evaluate the effectiveness of aerobic digestion in volume reduction and biosludge stabilization. These parameters are discussed in detail in the following subsection.
4.2. Experimental Plan

A batch set-up is also referred to as a die-out design where aerobic bacteria are put in a non-limiting environment given that the supply of oxygen is in excess allowing for maximum oxidation rate of Volatile Suspended Solids (VSS) [11]. Furthermore, other performance critical parameters like pH and temperature are kept within optimal range to eliminate their effect. To study the performance of a batch reactor, chosen response variables are tested and monitored relating to the main focus of this study. These variables include the digestion rate of aerobic bacteria which is tested through monitoring the reduction rate in solid content especially VSS through testing Volatile Solids (VS) destruction, Chemical Oxygen Demand (COD) destruction as well as other indicative parameters [37].

4.2.1. Solid Content Analysis

Since the drop in solids content achieved by aerobic digestion is the main focus of this research’s experiments, it is important to understand the solid content breakdown within biosludge and monitor solids’ components behaviors.

The term solid refers to the quantity of solid matter remaining in a sample after drying or igniting it at a specified temperature [38]. There are three categories of solids; Total Solids (TS), Suspended Solids (SS) and dissolved solids. Each category is made up of a volatile phase and a fixed phase. The interrelation between the different categories is illustrated in figure 15.

![Figure 15: Solids Content Breakdown](image-url)
The interrelation between solids categories can be further illustrated through equations 6 to 11. TS is the material residue left in a crucible after evaporation of a sample. Settleable solids on the other hand, are solids that settle naturally by gravity when left to settle in an Imhoff cone for one hour [28]. TS content can be classified in one of two ways; suspended and dissolved or as volatile and fixed. It can be analyzed as a lump sum through evaporating the biosludge sample in a weighed crucible and drying it at 104°C. The increase in weight over that of the empty crucible represents the TS [38]. The TS concentration derived through this experimental procedure can be verified by adding the TSS and Total Dissolved Solids (TDS) values or Volatile Total Solids (VTS) and Fixed Total Solids (FTS) values derived from separate experimental analysis, as illustrated in equation 22.

\[ TS = TSS + TDS = VTS + FTS \]  \hspace{1cm} (22)

Differentiation between TSS and TDS is accomplished by means of filtration. TSS, as the name entails, are solids that would not settle by gravity but instead stay in suspension hence, a vacuum pump is used for suction to collect SS on filter paper. What passes through the filter is the dissolved phase while the filtrate is what is held by the filter paper. TSS concentration is found by filtering the sample through a pre-weighed glass fiber filter. The filter paper is dried at 105°C and re-weighed. The amount of SS is determined by the increase in weight of the filter paper [38].

Most of the solid matter in biosludge is in the suspended form while the dissolved phase of solids is of minor significance. VSS and Fixed Suspended Solids (FSS) derived from TSS are related to the amount of inorganic and organic matter present in the solid fraction of wastewater, activated biosludge and industrial wastes, their determination is useful in the control of WWTP operations [38].

TSS content is made up of VSS and FSS, as illustrated in equation 23. The filtrate retained on a no-ash glass fiber filter disc of approximately 0.45 µm pore size from the determination of TSS is ignited at 550°C in a muffle furnace. Solids remaining after ignition are the FS, while the weight lost on ignition represents the volatile solids. Loss in weight is due to conversion of organic matter to CO₂ and H₂O [38].

\[ TSS = VSS + FSS \]  \hspace{1cm} (23)

Likewise, TDS are made up of Volatile Dissolved Solids (VDS) and Fixed Dissolved Solids (FDS) as illustrated in equation 24. The filtered solution resulting from TDS determination is collected in pre-weighed crucible then ignited at 180°C in a muffle furnace. Solids remaining after ignition are the FS, while the weight lost on ignition represents the volatile solids.

\[ TDS = VDS + FDS \]  \hspace{1cm} (24)

To verify the TS value derived from the first parameter experiment, VSS and VDS values from equations 23 and 24 are added to give VTS. While, FSS and FDS values
from equations 23 and 24 are added to give FTS. Finally, the summation of VTS and FTS gives TS. Such relations are illustrated in equations 25, 26 and 27.

\[
V_{SS} + V_{DS} = V_{TS} \quad (25)
\]
\[
F_{SS} + F_{DS} = F_{TS} \quad (26)
\]
\[
V_{TS} + F_{TS} = T_{S} \quad (27)
\]

The determination of TSS, VSS and FSS of activated biosludge is of paramount importance to this research since such parameters are conventionally considered for investigation of aerobic digestion [11].

Samples tested for solids content were the influent samples used to seed the reactor before operation and the effluent samples after aborting reactor operation. At a specified SRT of one week, samples are withdrawn from the reactor on a weekly basis to analyze for solids content. The American Public Health Association (APHA) and American Society for Testing and Materials (ASTM) standard methods were referenced to in carrying out the experiments. APHA 2540D was followed for testing TSS and APHA 240E was used for testing VSS and FSS content. APHA 2540B was used for analyzing TS.

4.2.2. Chemical Oxygen Demand (COD)

Although VSS is a good indicator for organic matter present in biosludge, COD determinations provide another measure of organic matter worth analyzing. For the purpose of this research, Total COD (TCOD) is analyzed for all samples. TCOD is constituted of the soluble and particulate matter of the biosludge. COD is a measure of the oxygen equivalent of the organic matter in a sample that is susceptible to oxidation by a strong oxidizing agent. COD measures those substances, which can be chemically oxidized. This test is widely used to measure the organic strength of biosludge samples, COD determination involves reacting the sample with an excess amount of an oxidizing agent for a specified period of time, after which the concentration of unreacted oxidizing agent is usually determined by a redox back-titration. The quantity of oxidizing agent used up is determined by the difference from the initial oxidant concentration. COD is reported in terms of oxygen equivalent. There are a number of different experimental procedures for measuring COD. Nowadays, the most widely used method involves refluxing the sample with an excess of potassium dichromate (K$_2$Cr$_2$O$_7$) [38]. Given the lab facilities for this research, TCOD was investigated for using a Hach kit, which follows the APHA 5221 standard method. All three samples were analyzed; the influent, samples from the mixed reactor throughout the lifetime of the experiment and the effluent sample.
4.2.3. Monitoring Parameters

Monitoring parameters are parameters that need to be continuously or periodically monitored throughout the experiment lifetime to ensure that process control parameters are within healthy range and digestion is proceeding effectively.

Monitoring parameters include pH, which is one of the most important measurements commonly carried out as part of environmental analysis. It is a way of expressing the H⁺ concentration of water and it is used to express the acidic or alkaline nature of a solution [38]. It should be controlled in the range of 7.0-8.0 to ensure optimal operation of the aerobic digestion process. In some cases inadequate pH is considered inhibitory to the process [15]. It is measured using a typical pH probe.

Another important parameter is the DO concentration that should be maintained in the 1-2 mg/L range to eliminate its effect on the digestion process [6] [4]. All aerobic life forms, including aquatic ones, require oxygen for respiration. Hence it is imperative for aerobic bacterial activity. It is a function of temperature, pressure, salinity and biological activity [38]. It should be maintained at an optimal concentration to ensure effective digestion. DO concentration was tested for using a designated probe.

Finally temperature was maintained in the 18°C-21°C ranges being a major parameter that is dependent on fluctuating weather conditions and hence; should be monitored and controlled. Lower temperatures should be avoided as they retard the process. Therefore a system should be designed, like a water jacket, to minimize heat losses where subsurface aeration is used [15]. Furthermore, k_d was observed to increase with digestion temperature. The mesophilic range is between 5°C and 40°C. An increase in temperature translates to a higher rate of reduction in solids and COD [11].
4.3. Results

4.3.1. GTL Biosludge Characterization

Biosludge characteristics vary widely due to the large variation of industries producing such waste. For each application, the optimal treatment train is chosen to treat the biosludge rendering it safe for reuse or disposal. For the case of GTL biosludge, samples were collected from the field and tested for organic content to check the suitability of digestion techniques in treating GTL biosludge.

It is difficult to determine the active biomass or biodegradable biological solids content directly. Consequently, the VSS concentration is conventionally used to determine the organic content [6]. The higher the organic content, the larger the drop in volume and the faster the stabilization achieved by digestion. Therefore, it can be deduced that the higher the concentration of VSS, the more effective digestion is at minimizing the solid content of biosludge and in turn stabilization of the final disposed waste and reduction of its total volume.

For the purpose of this study, aerobic digestion was investigated for the convenience of its implementation in the field. Aerobic digestion causes stabilization and volume reduction owing to the process of endogenous metabolism being its core activity [15]. Endogenous metabolism is a function of the active fraction of the bacterial population in biosludge [15]. Hence a drop in solids during aerobic digestion will only be due to a decrease in the active biomass or in other words the organic content in the digester. The decrease in inorganic or non-biodegradable organic solids would be negligible.

To characterize GTL biosludge, samples were collected from the SHT over the course of 3 months and then analyzed for solid content distribution. The plot depicted in figure 16 shows that regardless of the TSS concentration, the VSS content is more than 80% of the TSS. This proves that aerobic digestion is an optimal treatment technique for GTL biosludge stabilization and volume reduction, since it acts on the VSS content.
To further prove that the drop in TSS is owed to the decrease in VSS, the VSS/FSS breakdown of TSS for the chosen reactor is monitored as in figure 17. The FSS concentration should be immune to the aerobic digestion process being non-biodegradable and hence FSS concentration was expected to stay constant throughout the duration of the experiment. FSS concentration stayed at about 1,400 mg/L with an acceptable tolerance range of ±5% by weight for the first 7 weeks proving that any drop in TSS is owed to the volatile portion of the solid content.
The sudden drop in FSS concentration in week 8 is too notable to attribute to experimental errors, given that precautions were taken through standardizing sampling procedure and integrating dilution factors hence, eliminating sampling and dilution as sources of error in this case. A plausible explanation would be investigating the FSS concentrations versus corresponding FDS concentrations such that maybe FSS is broken down into the FDS phase throughout the digestion or solubilization process. To investigate whether the drop in FSS can be owed to a rise in FDS, the figure 18 was constructed as a form of mass balance between the two phases of FTS.

Figure 18 shows FDS rising in weeks 8 and 9 from constituting around 20% of FTS to making up a little over 30% of FTS. This supports the hypothesis that FSS is not affected by aerobic digestion but for weeks 8 and 9, it was converted from the suspended phase to the dissolved phase possibly through solubilization.
Other studies show that solids reductions during the experiments were essentially due to VSS reductions and the FSS concentrations remained more or less unchanged. In the digestion period, irrespective of the initial solids concentrations, solids reduction varied from 35 to 40% for VSS and 30 to 35% for the TSS. This 5% difference was observed only in case of low concentration activated biosludges, which is probably due to little amounts of absolute quantities of the biosludges. In absolute terms however, the solids destruction per unit volume of the digester increased with initial solids concentration, and thus allowing for very high destruction capacity per unit digester volume [11].

Endogenous metabolism causes a decrease in solids during aerobic digestion, which is owed to a decrease in the active biomass in the digester. However, the TSS can describe the digestion progress. Total COD reductions of such a biosludge undergoing aerobic digestion indicate the biodegradable part of the biosludge and also therefore indicate the progress of aerobic digestion [11].

Furthermore, this study’s optimization model uses the DS percentage drops, being more concerned with dry content versus moisture content. Hence, TS results derived from these experiments were fed into the model and are considered a good representation since a drop in TS is owed to a drop in the volatile content.
4.3.2. **Aerobic Digester (AD) Lab Results**

Primarily physical properties of the samples withdrawn from the best performing reactor were noted and documented on a weekly basis over the course of nine weeks. It was noted that initially biosludge was thick to the point of viscosity, black in color and produced an unpleasant odor. After several weeks of aerobic digestion, the biosludge was more diluted and watered-down; light brown in color and odorless. To better observe the effect digestion had on color, initial and final samples were filtered and the color of filtrates was compared. The filtrate of the influent sample had a yellowish liquid and the filtrate of the effluent samples was a relatively clear filtrate.

All solid content parameters were monitored where two samples were collected on a weekly basis and the average of both samples was taken as a representative of the measurement. Figure 19 shows TS, TSS and VSS concentrations drop over the course of the whole operation where drops of 62%, 72% and 74% were respectively achieved. This is a considerable drop in concentration that is sure to reflect on a good reduction in total volume of biosludge to be disposed of in the landfill. TS and TSS follow the trend of VSS indicating the volatile content to be the cause of drops in volume. The drop in VS content is expected to level off as time progresses indicating that a point has been reached when further digestion is no longer necessary, as more time will cost more and not achieved a considerable drop. This is shown as the rate of drop after week 7 is not as considerable as in earlier weeks.

![Figure 19: Drop in SS over the course of the experiment](image)
Another aspect to consider while analyzing the reduction in solid content is to map out the percentage removal rate for TS, TSS and VSS. The percentage removal at every time stamp is calculated with reference to the initial concentration. Figure 20 shows an insistent increase in removal rate from around 10-20% in early weeks to around 60-70% towards the end of the experiment.

![Figure 20: Solids Removal Rate vs. AD Residence Time](image)

Moving on to TCOD analysis, as it is an important digestion indicator as well as being the primary parameter used in the WWTP reports. There is a relation between TCOD and VSS specific to GTL biosludge where TCOD=1.42 VSS. Figure 21 confirms this relation as TCOD is almost 1.4 times more than VSS concentrations throughout the lifetime of the experiment. TCOD drops by 75% over the course of 9 weeks. TCOD was a useful indicator for assessing effectiveness of aerobic digestion as a treatment technique when it comes to using the plant’s terminology or parameters of interest.
It is also worth looking at the percentage rate of removal of TCOD over time. As was the case for solids, figure 22 shows that TCOD removal rate rises from around 30% to over 70% which is definitely agreeable but needs to be fortified with further experiments and compared to other treatment systems to be put in perspective as well as being studied on the economic front.
Besides monitoring the temperature to be in the range of 18°C and 21°C and the DO to always exceed 2 mg/L, the pH was monitored to ensure that an optimal environment is provided for effective aerobic digestion of biosludge. A pH level between 7.0 and 8.0 is considered optimal to yield minimum digestion time as well as maximum values of kinetic rate constants and in turn the highest performance \[11\]. Figure 23 shows pH levels comfortably varying within the acceptable ranges.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure23.png}
\caption{pH levels over the course of the experiment}
\end{figure}

4.3.3. Decay Constant (\(K_d\))

The main aim of running those experiments is to derive the GTL biosludge specific decay constant to be fed into the optimization model. The decay constant was derived from the best performing reactor results being a good representation of other reactors. It is assumed experiments were run at a temperature of 20°C hence the derived \(k_d\) is mapped to this temperature.

To derive \(k_d\), the change in solids content can be represented by a first order biochemical reaction represented by equation 28 \[11\]:

\[\frac{dX}{dt} = -k_dX\] \hspace{1cm} (28)

Where:
\[dX/dt = \text{rate of change of solids per unit of time, mg/L/d}\]
\[k_d = \text{reaction rate constant, d}^{-1}\]
\[X = \text{concentration of solids content remaining at time } t \text{ in the aerobic digester, mg/L}\]
\[t = \text{time, d}\]

Making \(k_d\) subject of equation 28 gives equation 29 \[30\],

\[k_d = -\frac{dX}{X_0 dt}\] \hspace{1cm} (29)
Equation 29 can be transformed into equation 30 below by integrating both sides,

\[ X_t = X_0 e^{-kd_t} \quad (30) \]

Where;
\( X_t \) = cell mass at time \( t \) (mgVSS/L) and
\( X_0 \) = initial cell mass (mgVSS/L).

To find \( k_d \), \( X_t \) values are collected at different points in time throughout the course of the aerobic digestion experiment while noting the \( X_0 \) value at the beginning of the experiment. Collected values are then used to plot equation 31. Slope of the line is \( k_d \) value for the biosludge at hand.

\[ -\ln \left( \frac{X_t}{X_0} \right) = k_d t \quad (31) \]

The reaction rate term \( k_d \) is a function of biosludge type, temperature and solids concentration [26].

Equation 31 can be applied to the different solid content concentrations including TS, TSS and VSS and in turn derive the matching \( k_d \) value. However, \( k_d \) is typically derived for VSS as the biodegradable volatile content but for the purpose of this study the decay constant derived for TS is used for the optimization model to find the degree of drop in DS content when biosludge is fed into the AD stage.

The results for the drop in TS over the course of the experiment are detailed in table 2. To plot equation 31 and find \( k_d \), the column \( \ln(X_t/X_0) \) was calculated.

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>TS (mg/L)</th>
<th>% drop in TS</th>
<th>( \ln(X_t/X_0) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>t0</td>
<td>10,498</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t1</td>
<td>7</td>
<td>9,227</td>
<td>12%</td>
</tr>
<tr>
<td>t2</td>
<td>14</td>
<td>9,983</td>
<td>5%</td>
</tr>
<tr>
<td>t3</td>
<td>21</td>
<td>8,182</td>
<td>22%</td>
</tr>
<tr>
<td>t4</td>
<td>28</td>
<td>7,624</td>
<td>27%</td>
</tr>
<tr>
<td>t5</td>
<td>35</td>
<td>6,603</td>
<td>37%</td>
</tr>
<tr>
<td>t6</td>
<td>42</td>
<td>5,911</td>
<td>44%</td>
</tr>
<tr>
<td>t7</td>
<td>49</td>
<td>4,898</td>
<td>53%</td>
</tr>
<tr>
<td>t8</td>
<td>56</td>
<td>4,502</td>
<td>57%</td>
</tr>
<tr>
<td>t9</td>
<td>63</td>
<td>3,986</td>
<td>62%</td>
</tr>
</tbody>
</table>
The plot in figure 24 was drawn to find the best-fit line for the data points and find the slope which is the $k_d$ value at 20°C.

![Figure 24: Plotting Biosludge Digestion Equation using TS to find Decay Constant](image)

Given an R-squared value of 0.947, it is reliable to use the $k_d$ value of 0.0145 at 20°C and then derive the $k_d$ values corresponding to different temperatures for the optimization model.

For the purpose of this study, temperature variations were not possible due to limited lab facilities hence, it was monitored to stay within a certain range to allow for the derivation of a $k_d$ value at 20°C. It is then derived for temperature variations in the optimization model using a designated equation as shown in earlier chapter.

Furthermore, $k_d$ values for TSS and VSS were derived as illustrated in figures below just to put the GTL biosludge characteristics in perspective in reference to literature findings for $k_d$ values extracted for various types of biosludge which were further discussed in the literature review section. The $k_{d,TSS}$ for GTL biosludge is derived to be 0.0181 day$^{-1}$, as shown in figure 25, while $k_{d,VSS}$ for GTL biosludge was derived as 0.0196 day$^{-1}$, as shown in figure 26.
The optimization model uses the decay constant derived for Total Solids (TS) since the design of the treatment units is based on DS content which is the TS content.
Chapter 5: Optimization of Biosludge Management System
This chapter details the development of the optimization model with special emphasis on managing GTL biosludge. It presents an overview of the model, sizing of treatment units and cost functions.

5.1. The Optimization Model

The main aim of this thesis is to develop an optimization model to obtain the optimum design for a management system of biosludge. The model emphasizes the management of biosludge generated from treatment plants treating the wastewater from Gas-To-Liquid (GTL) plants. It simulates the performance of the treatment units making up a GTL biosludge treatment line-up. Given a certain biosludge mass flux, flow rate and water to solid content ratio, the model tracks the performance of each unit in reducing the biosludge volumes and stabilizing its active biomass content. The model then produces the amount and quality of the treated biosludge that will either be disposed or reused. The model simulates the performance of the treatment line-up for a typical day averaged over one year taking into consideration the effect of seasonal variations on performance. The model has two main input variables where the designer varies the first keeping the second one constant. Each run produces a technically feasible alternative and calculates its associated costs. Since treatment cost is the objective function for this optimization model, the optimal alternative is chosen corresponding to the minimal cost. The optimal point for the first variable is then kept constant and the second variable is then varied to find the minimal cost alternative corresponding to a certain value of the second variable. This is the optimization search technique used to find the optimal alternative while taking into consideration that only technically feasible alternatives are considered.

The recommended treatment line-up for small-scale GTL plants includes three main units; Aerobic Digester (AD), Centrifuge and Drying Beds (DB). The design of the modules is dictated by two main variables; the residence time spent by the biosludge in the AD and the number of days a biosludge batch is left in the drying beds. These are the input variables that are varied alternatively by the designer to generate alternatives. Based on such inputs, the units are sized and their performance simulated. For example, varying the residence time in the AD translates into a certain tank volume defining an alternative design. The simulation sub-model is run on a daily basis over one year to assess the performance of the technically feasible alternative under consideration accounting for the effect of environmental factors. Temperature variations at the site of the treatment plant affect the performance of the AD and the drying beds through varying decay rates and evaporation rates. It is worth noting that an alternative could be rejected as unfeasible after the whole simulation is run.

System constraints that render an alternative technically feasible or unfeasible include the final application that biosludge will be channeled to whether it be disposal in landfills or reuse in land application. Each option has a set of environmental legislative constraints that need to be met by the produced biosludge.
The model is responsible for deriving the amount of biosludge produced from the line-up and its associated costs for each alternative design resulting from a different input. The main objective function is to minimize the total cost of a design alternative. Design alternatives are generated through varying two main decision variables; the residence time of biosludge in the tank (t) and the number of days spent in the drying beds stage. The total cost \( (C_{\text{tot}}) \) includes capital costs of AD tank construction, aeration equipment, centrifuge unit and drying beds construction. Operating costs include power consumption costs needed by aeration units, centrifuge and leaching systems. Operating costs also include polymer costs, trucking costs and landfill disposal tariffs.

The designer retrieves such performance and cost results for each alternative to plot a curve that allows him to choose the optimal alternative for the studied plant.

5.2. Design of System Components (Sizing of Treatment Units)

This section illustrates the sizing of the modules that make up the biosludge treatment and management system, which may vary according to the biosludge influent.

5.2.1. Aerobic Digester

The Aerobic Digester (AD) is designed based on the design volume flow rate of the inflow biosludge \( Q_1 \) and its Dry Solids (DS) contents.

Under the design \( Q_1 \), in \( m^3 \) per day, the effective volume \( (V) \) of the AD, in \( m^3 \), should ensure a design residence time \( (t) \) in days, as per equation 32.

\[
\begin{align*}
\text{Volume } V \ (m^3) &= \text{Flow rate } Q_1 \ (m^3 /d) \\
&\times \text{Residence Time } t \ (d) \\
&= \frac{t (d) \times Q_1 (m^3 /d)}{32}
\end{align*}
\]

The size of the AD tank \( (V_{\text{over}}) \) exceeds the effective volume \( (V) \) to allow for a free board in depth \( (FB) \) of 500 mm to 750 mm where \( (H_{AD} = D + FB) \). A common total depth \( (H_{AD}) \) of AD tanks ranges between 6.0 m and 9.0 m and it is typically chosen as 6.5m [4]. Equation 33 can be used to select the base area \( (A_B) \) of the AD which is its land footprint needed for its construction. Typical digester tanks are circular therefore the actual required land areas are slightly larger to allow for access tracks between treatment units.

\[
\begin{align*}
\text{Tank Volume } (V) &= \text{Area of base } (A_B) \times \text{Tank Depth} (H_{AD}) \\
&= \frac{t (d) \times Q_1 (m^3 /d)}{33}
\end{align*}
\]

It is worth noting that if the chosen footprint chosen footprint is relatively large, the effective volume can be split up into two AD tanks operating in parallel to facilitate maintenance of the aeration system.
Aerobic digesters should be equipped with an efficient aeration system. A dissolved oxygen (DO) concentration of above 2mg/L must be uniformly maintained throughout the tank volume to ensure aerobic conditions and in turn effective digester performance [6]. The amount of oxygen needed to oxidize a certain amount of organic matter (VSS) is based on equation 34 [15].

\[ C_5H_7O_2N + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3 \] \hspace{1cm} (34)

Under prolonged periods of aeration, NH\textsubscript{3} is further oxidized as shown in equation 35 [15].

\[ C_5H_7NO_2 + 7O_2 \rightarrow 5CO_2 + 3H_2O + H^+ + NO_3^- \] \hspace{1cm} (35)

Hypothetically, equation 35 indicates that 0.898 kg of oxygen is required to oxidize 0.45 kg of cell mass. Calculating the mass of volatile content and applying this relation, the mass of oxygen needed per day is found in kilograms.

The aeration system of the AD is comprised of an air blower, a piping system and air diffusing equipment. The airflow rate should be adjusted to ensure the supply of the required oxygen concentrations. Hence, appropriately sized air blowers supply the airflow. Air is supplied to the biosludge through diffusers that are uniformly spread at the bottom of the tank to ensure effective aeration and the maintenance of the required DO concentration. For aerobic digestion, an airflow rate of 20 to 60 ft\textsuperscript{3}/min is needed for every 1000 ft\textsuperscript{3} of biosludge volume in the tank [15]. For the purpose of this model, an airflow rate of 20 ft\textsuperscript{3}/min is supplied for every 1000 ft\textsuperscript{3} of biosludge volume in the tank. Consequently, as the residence time chosen by the designer increases for a constant flow rate of biosludge, the volume of the AD tank increases and a higher airflow rate will be needed. All units are converted to m\textsuperscript{3}/d and m\textsuperscript{3} to allow for uniformity of use of SI units however, the flow rate is then converted back to SCFM (standard cubic feet per minute) since it is the standard airflow rate unit of measurement used for blowers.

The appropriate blower power rating must match the needed airflow rate required for the AD and can be estimated using equation 36 [39]. Equation 36 empirically relates the blower power (P\textsubscript{w}) in hp to the airflow rate in SCFM.

\[ \text{Blower Power } P_w (hp) = 0.0517 \times \text{Air Flow Rate (SCFM)} + 0.8849 \] \hspace{1cm} (36)

The blower power then dictates the capital and operating costs needed to aerate a given volume of biosludge for a chosen residence time.

To calculate the number of diffusers needed to relay the airflow from the blower and spread it across the volume of the tank, there are two methods. First is using typical values for the density of diffusers, which range between 4.5 and 20 where equation 37 is used [40].
\[ \text{Density of diffusers} = \frac{\text{Number of diffusers}}{\text{Base Area of Tank}} \] (37)

The other method, used for this study, is using the airflow rate per diffuser disc which typically ranges between 0.5 and 4.5 SCFM and is chosen as 3 SCFM for this model hence equation 38 is used to find the number of diffusers [41].

\[ \text{Number of diffusers} = \frac{\text{Air Flow Rate of System}}{\text{Air Flow Rate of Diffuser}} \] (38)

Given the considerable volumes of biosludge addressed in the AD and due to learnings from the lab experiments, agitation equipment are recommended for aerobic digesters. A power of 1.25 hp is needed per 1000 ft\(^3\) of volume [15].

5.2.2. Dewatering Unit (Centrifuge)

The purpose of the dewatering unit is to decrease the moisture content of the biosludge and in turn reduce the overall volumes of biosludge produced from this stage i.e. producing biosludge with higher solids concentration. Centrifuges result in significant reduction in sludge volume that reduces the cost of subsequent treatment and disposal stages.

Biosludge out of the AD is fed into the centrifuge at the same biosludge flow rate per day since no content is lost during the AD operation. This is an assumption since some water is lost through evaporation but it is a negligible percentage of the total volume and is hence disregarded for the purposes of this model. However, the composition of the biosludge changes due to the effect of digestion that causes a drop in DS content and an increase in the moisture content. The percentage drop depends on the residence time in the aerobic reactor.

The sizing of the centrifuge or its power rating depends on the volumetric flow rate of biosludge into the centrifuge unit and is independent of the dry solid content. Taking a flow rate equivalent to 360 t/d, for example, would require a centrifuge rated at 66 GPM where Gallons Per Minute (GPM) is the unit typically used for centrifuges in the market and a flow of 66 GPM maps to a power rating of 55hp [42]. Furthermore, the centrifuge is set to achieve a certain degree of dryness given a certain range of DS content of influent sludge. A centrifuge typically produces a biosludge cake of dryness ranging between 15\% and 25\% for an inflow of 2-5\% DS content [43]. However, the variation of solids concentration in the feed does require different amounts of polymer to achieve the required % DS content, as illustrated in chapter 3.

5.2.3. Drying Beds

After dewatering in the centrifuge, the biosludge cake is channeled or transported by trucks to the drying beds area. Drying beds are paved areas of land equipped with
proper leaching systems to handle drained water. The paved area is divided into smaller beds of equal areas where the daily batch of biosludge is moved from one bed to the other on a daily basis to allow for proper turning and aeration, increase evaporation rates and prevent the release of odors. Typical biosludge handling in drying beds involves its turning and aeration within the same bed however, moving a biosludge batch from one bed to another was the method adopted for this design to achieve turning and aeration purposes. Figure 27 shows a typical drying beds construction layout [20].

![Figure 27: Drying Beds Design](image)

Typical sludge thickness is between 20-30 cm and is chosen as 25cm for this design [21]. Each cell or drying bed typically has a width of 6 meters. The length of each cell can then be estimated from equation 39 [4].

\[
\text{Area of one bed} = \frac{\text{Volume of a daily batch of biosludge}}{\text{Sludge layer thickness}} = \text{Length of bed} \times \text{Width of bed} \quad (39)
\]

The number of beds is equal to the number of days the biosludge is left to dry since the batch is moved from one bed to another. This is a decision made by the designer based on the percent dryness that needs to be achieved to meet landfill requirements, environmental standards or economy.
5.3. The Simulation over One Year

The simulation sub-model illustrated in chapter 3 is applied to simulate the daily performance of the alternative design under consideration for one full year (365 days). The output for each day differs due to variations in ambient temperature, which affect the rates of decay achieved for a constant residence time in the AD as well as the evaporation rates occurring in the drying beds for a constant period. Hence the amounts of treated biosludge produced vary from one day to another, which directly affects the operating costs of polymer addition, trucking and disposal. The model produces an average annual unit cost per ton taken over one year as a representation of the cost (objective function) of a given alternative.

5.4. Cost Estimation Methods

To quantify the optimization process, it is imperative to realize the investments made for each scenario to direct the decision to the most economical and technically feasible scenario taking into consideration customer preference. Hence, cost functions that vary according to the treatment units sizing options were developed to derive the unit cost of handling one ton of biosludge over an annual average performance, i.e. the objective function.

5.4.1. Capital Expenditure (CAPEX)

CAPEX are initial investment costs that are spent as a lump sum early on in the project and their costs are divided up on an annual basis to derive a representative figure for the unit cost of handling one ton of biosludge. The Cost Recovery Factor (CRF) formula in equation 40 was used to find the annual CAPEX for each cost item where CRF is multiplied by the CAPEX to give the annual cost which is then divided by the number of days in a year to find the cost per day. The average cost per day is then divided by the amount of inflow biosludge produced per day to find the unit cost per ton.

\[
CRF = \frac{i(1 + i)^n}{(1 + i)^n - 1} \quad (40)
\]

The interest rate is taken by default as 10% while n, which is the engineering lifetime of the unit, is taken as 50 years for land and civil works items and 15 years for electro-mechanical equipment cost items.

Costs for the civil works are estimated from empirical cost functions. The cost of land required constructing the AD, and drying beds is related the unit cost of land \(C_l\) in the area where the plant is constructed and the foot print of the civil works \(A_B\) and \(A_{DB}\), as in equation 41.
\[ Cost \ of \ Land \ (\$) = C_l \left( \frac{\$}{m^2} \right) \times A_B + A_{DB} \ (m^2) \] (41)

The cost of the concrete AD tank including materials and construction is estimated by equation 42 which relates the cost of the tank to unit cost of concrete tanks \( C_{tank} \) (\$/m\(^3\)) of sludge volume and the bio-sludge volume (m\(^3\))

\[ Cost \ of \ Tank \ (\$) = C_{tank} \left( \frac{\$}{m^3} \right) \times Volume \ of \ tank \ V_{tot} \ (m^3) \] (42)

Blower costs are expected to increase linearly with an increase in power rating as shown in equation 43 [44].

\[ Blower \ (\$) = C_{Blower} \left( \frac{\$}{KW} \right) \times Power \ rating (KW) \] (43)

The cost of diffusers and in-tank piping \( Cost_{Diffuser} \) is estimated from equation 44 which relates the numbers of diffusers \( N_{Diffuser} \) and the cost of a single diffuser including its piping \( C_{Diffuser} \). Since diffusers are replaced very frequently hence, their CRF is based on a smaller life time of typically 5 years [45].

\[ Cost_{Diffusers} (\$) = C_{Diffuser} \times N_{Diffuser} \] (44)

The cost of the aeration piping from the blowers to the AD tank(s) and their control valves are assumed to be equal to the cost of the diffusers.

The cost of mixer \( Cost_{Mixer} \) can be estimated based its unit cost \( C_{mixer} \) and the power of the mixers \( P_{mixer} \) installed in the AD tank(s) as in equation 45.

\[ Cost_{Mixer} (\$) = C_{mixer}(\$/KW) \times P_{mixer}(KW) \] (45)

Given the constant flow, the centrifuge sizing does not vary with the variations in residence time and ambient temperature, hence the 66GPM centrifuge cost is $50,000 for the required rate [32].

Drying beds have a CAPEX of land and construction costs with the same rates used for the AD in equations 41 and 42. Also, the leaching and drainage system will have an average cost that is 40% of the drying beds construction cost.

5.4.2. Operating Expenditure (OPEX)

The operating costs vary from one day to another (typical of each month), hence the OPEX is calculated for every month and then an average is taken over one year to find the annual costs which are used to find the unit cost per day and in turn the cost per ton.
The monthly rate for a continuous operation of aeration equipment, mixer and centrifuge will be calculated as follows with the addition of an annual maintenance cost of 10 percent of their capital cost in equation 46.

\[
OPEX \text{ for equipment (\$)} = \text{Power rating (KW)} \times C_{power} \left( \frac{\$}{\text{KW}\text{hr}} \right) \times 24\text{hrs} \times 30\text{days} \quad (46)
\]

In addition, the OPEX also includes the cost of polymers used by the centrifuge to reach its target concentration of 18 percent. The unit cost of polymers used for every ton of inflow dry solids to the centrifuge is $12 [32].

The OPEX also includes the cost of moving the sludge cake from the centrifuge to the drying beds if located at an available location different from the treatment plant. In the drying beds, biosludge is turned on a daily basis and moved from one bed to another. The cost of this operation is added to OPEX. If the final dried sludge produced from the drying bed is to be disposed of to a landfill, then the OPEX should also include the tariffs ($/ton of sludge) for disposal.

The CAPEX and OPEX per ton figures are summed to give a numeric value of the objective function that reflects the performance of the alternative under consideration.
Chapter 6: Applications of the Optimization Biosludge Management System Model
The optimization model of the biosludge treatment line-up has two main variables, as mentioned earlier. Both variables aim at reducing the unit treatment costs through minimizing the volume of biosludge being disposed of in the landfill while ensuring an acceptable degree of stabilization.

Varying the residence time spent by the biosludge in the Aerobic Digester (AD) tank, while keeping the other variable constant, yields treatment alternatives with different unit costs. The chosen point is preferably the minimal cost point unless other environmental legislations dictate the validity of one alternative over the other. Increasing the residence time of the aerobic digestion stage affects the volume of dry solid content going through the centrifuge and the drying beds and ultimately disposed of in the landfill. An increase in residence time reflects as a reduction in cost of dewatering, drying and disposal however, it also translates into an increase in costs due to the need for a larger AD tank and aeration equipment to accommodate for a longer residence time. Hence, the plant owner or designer should use this model to choose the minimum cost point which is a trade-off between the desired drop in dewatering and disposal costs and the affordable increase in AD costs taking into consideration variations in ambient temperature.

After choosing the optimal AD residence time, the designer keeps the first variable constant at the optimal value and starts varying the number of days biosludge is left to dry in the drying beds. Increasing the time biosludge is left in the drying beds reduces the final volume of the disposed biosludge, which in turn reduces the costs of trucking and landfill occupation. However, the design dictates that the number of days biosludge is left in the drying beds is equal to the number of drying beds since each batch is turned from one bed to another on a daily basis hence, the longer the time a biosludge batch is left in the drying beds, the higher the capital costs. Consequently, the minimum cost point is chosen such that the maximum dryness is achieved with minimal increase in cost.

Finding the minimum cost point achieved by each variable suggests the optimal design configuration for the treatment line-up.

The optimization model was tested using five cases as different applications to propose the optimal treatment line-up that offers a technically feasible alternative at minimum cost while taking into consideration the different constraints. The main application used for this study is GTL biosludge where lab experiments were carried out to derive its specific decay constant. The first three applications test GTL biosludge under different constraints. Applications 4 and 5 test the performance of the model using sewage sludge and biosludge produced from the refinery industry.
6.1. Description of the Case Study

The case study deals with the management of biosludge generated from a plant treating wastewater generated a Gas-To-Liquid (GTL) plant. The plant is located in the Gulf area, which is characteristic for warm arid climates. The GTL Wastewater Treatment Plant (WWTP) produces a constant daily biosludge mass flux of 360 tons. Samples of the biosludge show that it has 5% Dry Solids (DS) content, by weight. The VSS amounts to nearly 80 percent of the TS, as previously discussed in Chapter 4. The decay coefficient at 20 degrees is 0.0145 day \(^{-1}\). The WWTP is located in an area that has a high land cost of $450 per square meter \([46]\). There is no market for the reuse of processed biosludge for agricultural purposes, which makes disposal in landfills the recommended option. The cost of disposal in the landfill is $20 per ton.

The unit cost for the reinforced concrete used in constructing the Aerobic Digester (AD), and drying beds is approximately $200 per cubic meter of the volume of structures. The structural and hydraulic design of the AD recommends tank overall depth of 6.5 meters.

The AD tank is equipped with blowers, which are sized to supply airflow at a rate of 20 ft\(^3\)/min for every 1000 ft\(^3\) of the tank volume to maintain DO concentrations of 2 mg/L. Additional mixing is required for the AD with an estimated power of 1.25 hp for every 1000 ft\(^3\) of the biosludge. A sufficient number of diffusers should be installed across the AD base to ensure uniform aeration, with an estimated cost of $10 per diffuser and its in-tank supply pipes (C\(_{\text{Diffuser}}\)). The unit cost of the AD blowers and mixer (C\(_{\text{Blower}}\) and C\(_{\text{mixer}}\)) are taken as $200/KW. It is assumed that the diffuser lifetime is 2 years. The cost of off-tank aeration piping is assumed to be similar to the cost of diffusers. An annual maintenance cost of $5,000 for the blower, mixer and piping is added \([44]\). The running electricity costs of operating the blower, mixer and centrifuge (C\(_{\text{power}}\)) are taken as $0.07/KWhr.

A 66 GPM centrifuge is chosen to match the 360-ton biosludge flow rate with an estimated cost of $50,000 for the unit and its ancillaries. The centrifuge is chosen to produce a biosludge of 18% DS content by weight given the varying input solid content concentrations that range between 2% and 5% DS by weight. The estimated cost of polymer used by the centrifuge is $12 for every ton of influent DS to the centrifuge.

The biosludge management system may include drying beds annexed to the WWTP. The temperature profile for the area was used in the simulation. For the arid climate at the WWTP site, water evaporation rate from the sludge cake in the drying beds is estimated to be 7.7 mm/d in summer and 2.3 mm/d in winter \([47]\). Biosludge is turned from one bed to another on a daily basis depending on the design alternative of the drying beds with an associated cost of $10 per ton for labor and machinery.

A trucking cost of $20 per ton is charged to transport the biosludge to the disposal site.
6.2. Application 1: GTL Biosludge disposed of in Landfill with no constraints or standards

The first case can be considered the base case where there are no regulatory constraints for disposing GTL biosludge in the landfill hence; the only decision driver would be achieving minimal cost. It is assumed that the drying beds are located near the treatment plant where the resulting biosludge batch is then trucked to the landfill for disposal. The Aerobic Digester (AD) residence time is varied while keeping the number of days spent by a batch of biosludge in the drying beds set at 7 days, which is near to the maximum achievable dryness. A set of alternatives is produced corresponding to different AD residence times and the minimum cost point is chosen. The chosen point recommends a certain AD residence time that is kept constant while the number of days spent in the drying beds is varied to find the minimum cost corresponding to a certain number of beds. The model consequently suggests a treatment line-up based on the minimal unit cost alternative.

The drop in biosludge volume achieved by increasing residence time is illustrated in figure 28. It is evident that the longer biosludge is left in the aerobic digester, the smaller the volume of waste disposed of in the landfill. Biosludge sent for disposal dropped from a monthly average of 22.18 tons/day to 8.62 tons/day, which is a considerable drop in weight of about 61% in 42 days. The relationship is exponential and varies according to the GTL biosludge decay constant derived from experimental procedures discussed earlier.

![Figure 28: Amount of Biosludge to Landfill vs. AD Residence Time](image-url)
Figure 29: Unit Cost of GTL Biosludge Management vs. AD Residence Time

Figure 29 shows the increase in unit cost of management of one ton of the inflow biosludge as the residence time increases. The zero residence time point displayed on the curve indicates a treatment line-up that bypasses the existence of the aerobic digestion stage, i.e. the management system comprises only of centrifuge and drying beds prior to transportation to the landfill. It is evident that excluding the AD from the GTL biosludge treatment line-up for this set-up is in fact the minimum cost point.

Figure 30 shows the cost of each component of the management system at the different residence times. As the residence time increases, the capital and running costs of the AD increase at a much higher rate than the drop in dewatering and disposal costs. This recommendation is due to the low rate of decay of the GTL sludge ($K_d$ of 0.0145 day$^{-1}$), which results in costly AD tanks that do not correspond to sufficient reduction in the cost of the centrifuge, the drying beds, transportation to the landfill, and its disposal fees.
Figure 30 shows that the cost of dewatering using the centrifuge (Centri) and disposal (DB+LF) are higher than the cost of running the AD for smaller residence times of less than 2 weeks. In addition, the rate of increase in AD related costs is higher than the rate of drop in dewatering, drying and disposal costs achieved by longer AD residence times which can be seen in figure 30 as the small slope of the Centri and DB+LF when compared to the AD line. Furthermore, the increase in unit cost follows the trend of increase in AD costs very closely.

The minimum unit cost of biosludge management is $7.31 per ton with no AD stage i.e. the cost of dewatering and disposal. The unit cost then increases to $13.46 per ton after 42 days of residence time where dewatering and disposal constitute $3.54. It is true that 42 days of digesting biosludge achieved a halving in the cost of dewatering and disposal but at a considerable increase in total treatment costs by a factor of almost two, which reflects a drop in disposed biosludge weight by 61%. However, a cost driven recommendation would be eliminating the AD stage to produce an average annual amount of 22.18 tons of GTL biosludge sent to the landfill at a unit cost of $7.31 per ton.

The next step in running the model is eliminating the AD stage, which is the minimum cost point and varying the number of days spent in the drying beds. The number of days spent in the drying beds is varied between 1 and 8 days since 8 days achieves maximum dryness in summer months. The case of eliminating the drying beds stage has also been added as the zero days point which is obviously a very costly alternative. Figure 31 shows that the minimum cost is theoretically achieved when a daily biosludge batch is left to dry for 8 days causing a unit cost drop to $7.26 per ton.
Figure 32 shows the amounts of biosludge produced corresponding to varying the number of days spent in the drying beds. The minimum cost point corresponds to a drop in the amount of biosludge to landfill to 20.3 tons/day as opposed to 22.18 ton/day. The plot further confirms the criticality of including drying beds stage in the treatment line-up as spending only one day in the drying beds achieves a 64% drop in biosludge amounts to landfill which is owed to the 70% water lost to drainage occurring in the first day. It is also interesting to note that the benefits of an additional seven days recommended to dry the biosludge outweigh the costs invested to add seven more beds in terms of reducing the unit cost by $0.05 for every ton owed to a two ton reduction in disposed amounts.
The recommended treatment line-up is eliminating the aerobic digester stage and leaving the biosludge batch produced from the centrifuge to dry for 8 days before trucking 20.3 tons/day to the landfill site at a total cost of $7.26/ton. The design of the drying beds stage should include eight beds each with a surface area of 380 m² to maintain a bed width of 6m and a sludge depth of 250 mm as recommended.

It is worth noting that although the most cost effective model is to bypass the aerobic digestion stage be all together, it might not be the recommended solution because the advantages of AD are not limited to reduction in weight and cost minimization but also extend to stabilizing the quality of biosludge making it inactive and more suited for safe disposal or reuse in other applications. This function of aerobic digestion will be more evident in other cases when other constraints are introduced.

Furthermore, the designer or plant owner can use this model to decide on the cut-off point at which an acceptable cost is paid for an evident drop in biosludge volume as it is left to the user to choose the optimal point according to the case at hand. For example a considerable drop in volume of disposed biosludge may have an evident opportunity cost from, for example, an environmental or regulatory point of view when compared to the rise in costs caused by a longer residence time in the aerobic digester. Furthermore, in other set-ups the cost of land might not be as extensive when compared to the costs of disposal and dewatering as it is in this case and hence, a larger AD would be an optimal solution. On the other hand, there might be a case where the cost of running an AD is not affordable for operational reasons and hence, eliminating the stage of an AD would be the most cost effective option. This design model allows versatility enough to be tailored to the case at hand to allow the designer to find the most optimal solution that suits the case.
6.2.1. Seasonal Variations Consideration

It is important to put into consideration that all discussed figures are annual average values. However, the effect of ambient temperature on the performance of the AD and the evaporation rates occurring since it directly affects the decay constant. The drop in biosludge achieved at different AD residence times and its corresponding cost, is an annual average taken over the system’s performance over the twelve months. Figure 33 shows the actual performance achieved at different residence times ranging from zero to 42 days over the course of the year. The plot depicts a considerable drop in disposed biosludge in summer months of around 50% more than those achieved in the winter months since aerobic digestion is a process that favors an increase in temperature for optimal bacterial operation given that temperatures are within the mesophilic range, which is the case here. This however introduces a slight inaccuracy in the optimization model where the decision is based on an annual average that is not representative of such wide monthly variations. Increasing the effectiveness of the model can be achieved by having different residence times for different times of the year to achieve a constant biosludge output over the year for disposal. Such monthly variations are only reflected on the dewatering and disposal costs since the capital cost of the AD is fixed throughout the year and its aeration systems are continuously operating. Hence, substantial savings are made during the summer through disposal and dewatering but an overall performance is represented by an average unit cost.

On the other hand, the different evaporation rates causing variable performances in the drying beds do not have the same effect on performance as shown in figure 34. The difference in amounts of biosludge produced from one season to another is more evident for longer times spent in the drying beds where the biosludge is left to lose water through evaporation for longer periods of time. Hence, errors introduced by taking the annual average are more evident in such cases.

In both cases, a modular optimization model would allow for more accurate results that suggests different residence times for different months or seasons could be more representative of actual performance.
Figure 33: Seasonal Variation in Amount of GTL biosludge to Landfill for different AD Residence Times

Figure 34: Seasonal Variations in Amount of Biosludge vs. Days spent in Drying Beds
6.3. Application 2: Biosludge disposed of in Landfill to meet the EPA standard

The main concern of the first application was to consider cost minimization as the only objective function. Environmental and regulatory constraints on plant operation and disposal were not introduced. This application however dictates compliance with EPA standard 40 CFR Part 258 that was established to provide minimum national criteria for all solid waste landfills, assuming that a similar standard may be applied to the case study area [23]. The types of landfills regulated under Part 257 include those facilities that receive non-hazardous industrial waste only [23]. GTL biosludge qualifies as non-hazardous waste since it does not house any hazardous components. The standard dictates that leachate and emissions are closely monitored hence, it is beneficial to reduce the volatile content (organic content) to as low as possible [23]. Monitoring leachate and emissions is a costly process, not to mention targeting compliance with such standards is another costly task. Hence, an attempt to qualify for an exemption should be considered for smaller operations. The exemption from Subpart D (Design) is applicable only to owners or operators of landfill units that receive, on an annual average, less than 20 tons of solid waste per day [23]. Analyzing results depicted in figures 28 and 33 indicate the minimum AD residence time alternative that achieves the 20 tons per day threshold.

To comply with this exemption, the aerobic digestion stage proves pivotal in decreasing the volatile content as well as achieving the 20 tons per day threshold. Looking at the average weights of biosludge disposed per day, the 20 tons threshold is achieved after 4 days of residence time in the aerobic digester looking at the annual average curve depicted in figure 28.

Nevertheless, this decision is not fairly accurate since the average drop in disposed biosludge weight to below 20 tons is achieved in half of the year and surpassed in the other half of the year, as shown in figure 33. Hence, the optimal residence time to achieve the 20 tons threshold must take into consideration the largest amount of biosludge produced over the year i.e. the worst performing month. The standard would not be met, if at any one day the minimum threshold is not achieved. Analyzing figure 33, a residence time around 21 days would ensure that the produced biosludge would not exceed an amount of 20 tons per day costing $9.94 per ton. Hence, due to legislative constraints that render all alternatives less than 21 days invalid, the new minimal cost point is an AD residence time of 21 days.

The next step is keeping the AD residence time constant and varying the number of days spent in the drying beds to find the minimum cost point in such case. The plot shows that the minimum cost point occurs when biosludge is left for one day in the drying beds leading to a unit cost of $9.71 per ton as shown in figure 35. However, looking into the monthly performance of the drying beds shown in figure 36, biosludge must be left for 8 days in the drying beds are needed to get closer to the 20 tons threshold.
Hence, the recommended solution here is an AD residence time of around 21 days while leaving the sludge batch in the drying beds for 8 days costing $9.97 per ton. An AD tank of volume 8000m³ is needed to achieve a residence time of 21 days to maintain the recommended 6.5m tank height. The tank footprint needed is 1250m². Eight drying beds are needed, each with a surface area of around 240m² and depth of 0.25m.

![Figure 35: Unit Cost vs. Varying Days in Drying Beds (AD residence time constant at 21 days)](image)

![Figure 36: Effect of seasonal variations on Biosludge to Landfill for different Number Drying Beds](image)

This application further supports the recommendation of having a modular design for the optimization model where longer residence time is needed for winter months and shorter residence time is needed for summer months both in the AD and the drying beds to achieve the 20 tons per day threshold. Such a case would allow this set up to be more cost effective as not all months would need longer residence time for the same produced waste volumes.
6.4. Application 3: Biosludge to be reused for Land Application

For the case upon which this model was developed, the reuse of biosludge for land application was not a feasible option due to a lack of agricultural opportunities within the surrounding area. However, for other similar cases with a potential for biosludge re-use, the model can be used to obtain a different optimum design. To reuse biosludge for land application, the EPA 503 Class B standard has to be met. Hence, one of the suggested PSRPs must be used. Aerobic digestion is one of the processes accepted by this standard. It states that values for the mean cell residence time and temperature need to be around 40 days at 20°C (68°F) and 60 days at 15°C (59°F) [6].

Taking a more applicable measure into consideration, vector attraction reduction for aerobically digested biosludge is demonstrated either when the percent VS reduction during biosludge treatment equals or exceeds 38%, or when the specific oxygen uptake rate (SOUR) at 20°C (68°F) is less than or equal to 1.5 mg of oxygen per hour per gram of total solids, or when the additional VS reduction for bench-scale aerobic batch digestion is less than 15% for 30 additional days at 20°C (68°F) [6].

To find the drop in solid content achieved through aerobic digestion, a plot is drawn from lab results and derivations as shown in figure 37. A 38% annual average drop in solids is achieved at around 18 days. However, this does not meet the standard for winter months, hence the worst-case scenario of January must be considered, a 38% drop in solids is achieved at 28 days of AD residence time. Again having a modular design for the different months would require less time for summer months to achieve the required 38% and a longer residence time is needed for winter months allowing for cost savings at certain times of the year.

![Figure 37: Percent Drop in TS for GTL Biosludge vs. AD Residence Time for different months](image)
The model is run for an AD residence time of 28 days eliminating the landfill tariff costs resulting an annual average disposed amount of 11.72 tons per day costing $11.03 per ton. The next step is to keep the AD residence time constant at 28 days and vary the time spent in the drying beds to achieve lower costs. Figure 38 shows that keeping the sludge in the drying beds stage for just one day allows for minimizing the unit cost to $10.69 per ton.

Hence, the recommended treatment line-up to reuse GTL biosludge in land application is to have an AD residence time of 28 days and leave the biosludge in the drying beds for one day before trucking it to the reuse site. The amount of produced biosludge would be 16.9 tons/day and cost $10.69 per ton. The increase in amount from 11.72 tons to 16.9 tons is owed to spending less time in the drying beds for the sake of cost reduction bearing in mind that the required solid reduction has already been achieved in the AD stage while the drying bed stage just contributes to water loss. The annual average value of 16.9 tons/day would vary between seasons due to a variation in evaporation rates in the one day it spends in the drying beds however; it is not considerable and it will not defy the 38% drop in solids standard.

The suggested line-up requires a total AD tank volume of 10,000m$^3$, which is better to be split up into two equal 5000m$^3$ tanks running in parallel each with a footprint of 800m$^2$ to allow for a residence time of 28 days. One drying bed is needed with a surface area of around 200m$^2$ and depth of 0.25m.

Obviously, if there is a potential market for the re-use of processed biosludge in land application the management cost may be partly or fully reduced by selling the processed biosludge.

Figure 38: Unit Cost of biosludge treatment vs. Different Number of Drying Beds (at AD residence time 28 days)
6.5. Application 4: Applying the Model to Domestic Sewage Biosludge

The optimization design model was developed with an emphasis on managing GTL biosludge in areas with high land-value, warm climate and high landfill tariffs. However, it can be applied to manage biosludge resulting from treatment plants processing domestic sewage for a management system that would also comprise of aerobic digesters, centrifuge, and drying beds.

For biosludge generated from domestic sewage, the decay constant is taken as 0.05day\(^{-1}\) as opposed to a value of 0.0145day\(^{-1}\) for GTL biosludge [25]. A higher decay rate for sewage sludge is caused by the nature of high organic matter content as opposed to the GTL one. Figure 39 shows the final output sludge for both the GTL and domestic sewage treatment plants where the annual average drop in TS is greater for the sewage sludge than the GTL biosludge.

![Figure 39: Amount of Biosludge (GTL and Domestic) to Landfill vs. AD Residence Time](image)

The enhanced performance of aerobic digestion when applied to sewage sludge is clearly illustrated in figure 39. The same initial amount of 360 tons of sewage sludge drops to an annual average disposed amount of 1.09 tons per day after a residence time of 42 days while 360 tons GTL biosludge drops to 8.62 tons per day given the same AD residence time. Hence, the effect of aerobic digestion on sewage sludge is more evident as it achieves larger percentage drops in less residence time and consequently with less investment costs.

Running the model on sewage sludge where the number of days biosludge is left in drying beds is kept constant at 7 days and the residence time in the AD is varied, a minimum cost point is achieved as shown in figure 40. Unlike the case of GTL biosludge, adding the aerobic digestion stage actually reduces the cost from $7.31 to
$6.37 per ton for an AD residence time of 8 days resulting in 11.83 tons of biosludge to be disposed of per day. Figure 41 explains such behavior where that the savings achieved by volume reduction in the dewatering (Centri) and (DB+LF) disposal stages are achieved at a higher rate than the increase in cost due to longer residence times in the AD reactor. This is owed to the 0.05 day\(^{-1}\) decay constant of sewage sludge opposed to the 0.0145 day\(^{-1}\) decay constant of GTL biosludge. This application proved that aerobic digestion is more favorable for biosludge with higher decay constants.

Figure 40: Sewage Biosludge Unit Cost vs. AD Residence Time

Figure 41: Unit Cost Breakdown of Sewage Sludge Treatment for different AD residence times
After deciding on the minimal cost point for the AD residence time to be 8 days, this variable is kept constant at the recommended value and the time spent by biosludge in the drying beds is varied. Figure 42 shows that leaving the biosludge for one day in drying beds before trucking it to the landfill site achieves maximum reduction in cost to $6.01 per ton resulting in an annual average amount of 16.8 tons of biosludge to be disposed at the landfill.

![Figure 42: Unit Cost Breakdown vs. time spent in Drying Beds (at 8 days AD Residence Time)](image)

After running the model, the optimum treatment line-up recommends 8 days of residence time in the AD and one day for the biosludge is to lose water content in the drying beds resulting in an average annual of 16.8 tons per day costing $6.01 per ton. An AD tank volume of 3000m$^3$ with a footprint area of 470m$^2$ is needed to maintain the suggested residence time. The single drying bed has to have an average area of 170m$^2$ and a depth of 0.25m.

6.5.1. Applying Other Constraints

If the 20-tons threshold were applied to sewage sludge, the minimum cost point of 8 days in AD digester and one day in the drying beds would be sufficient to comply with the standard. Furthermore, 8 days in the AD digester does meet the requirement for the worst performing month. However, the worst performing month does demand an increase in time spent in drying beds will have to be raised to 5 days causing the costs to increase to $6.25 per ton but it is still significantly less than treating GTL biosludge to meet the standard. Unlike the case of GTL biosludge, which requires 21 days in the AD tank and 8 days in the drying beds costing $9.71 per ton as opposed to the $6 needed for sewage sludge. This exhibits the responsiveness of different types of biosludge to the proposed treatment train in minimizing cost.
Furthermore, if the 38% solids drop limit were applied for this case to qualify for land application, a residence time of 6 days would be sufficient to achieve the required annual average of less than 20 tons and taking the worst case scenario of January, a residence time of 9 days (as seen in figure 43) with one day in the drying beds amounting to a cost of $6.37 per ton. This is opposed to the 28 days of AD residence with one day in the drying beds required for GTL biosludge, which costs $10.39 per ton.

![Figure 43: Percent Drop in TS for Domestic Biosludge vs. AD Residence Time for different months](image)

Applying the constraints introduced in applications 2 and 3 to sewage sludge shows that a cost minimization is still possible for these environmental standards for cases of high decomposition rates since aerobic digestion seems to be most suited for such biosludge types.
6.6. Application 5: Applying the Model to Refinery Sewage Biosludge

Building on the conclusion drawn in the last subsection where the higher the decay constant, the more suited the model is in suggesting a minimum cost design. Accordingly, the model is applied to design a management system for biosludge produced from a refinery industry, which has a decay constant of 0.09 day$^{-1}$ [27]. Keeping the time spent in the drying beds stage constant and varying the AD residence time, a minimal cost design is found as shown in figure 44. An AD residence time of 8 days is needed to achieve a minimum cost of $5.14 per ton. The residence time is the same residence time required to achieve the minimum point for domestic sludge however, the cost minimization achieved by refinery sludge is more evident. This trend is owed to the higher decay constant of refinery biosludge, which reduced the cost of dewatering and disposal at a higher rate than the increase in aerobic digestion costs.

![Figure 44: Unit Cost of Refinery Biosludge for different AD Residence Times](image)

![Figure 45: Amount of Refinery Biosludge produced for different AD residence times](image)
The amount of biosludge produced for this minimum cost point is 7.31 tons per day, as shown in figure 45. Then, the AD residence time is kept constant at 8 days and the time spent in the drying beds is varied to find the overall optimum point for the system. The least cost is achieved when biosludge is left for one day in the drying beds amount to a unit cost of $4.55 per ton, as shown in figure 46.

![Figure 46: Refinery Biosludge Unit Cost for different Number of Drying Beds](image)

The optimal treatment line-up that receives 360 tons per day includes an 8 days AD residence time and one day in the drying beds producing an annual average amount of 10.2 tons/day of refinery biosludge sent to landfills at a unit cost of $4.55 per ton. An AD tank of volume of 3000m$^3$ with a footprint of 470m$^2$ is needed to provide a residence time of 8 days. The drying bed will occupy a surface area of 100m$^2$ and a depth of 0.25m.
6.7. Comparing Different Biosludge Types

In an effort to put the drawn results in perspective, the costs of the three studied biosludge types are contrasted. GTL biosludge has a decay rate of 0.0145 day$^{-1}$ while sewage sludge has a decay rate of 0.05 day$^{-1}$ and refinery sludge a decay rate of 0.09 day$^{-1}$. Figure 47 shows how running the model through varying the residence time recommends an 8 day AD residence time for high decay rate biosludge types to minimize cost while suggesting the elimination of the AD stage all together for GTL biosludge. The 8 day AD residence time recommended for sewage sludge and refinery sludge yields lower costs for refinery sludge showing due to its higher decay rate constant.

![Figure 47: Comparing Different Biosludge types vs. AD residence times](image)

This shows that this optimization design model is useful in detecting the minimal cost designs, and recognizing the benefit of each treatment unit of the management system.
Chapter 7: Summary and Conclusions
Biosludge is a solid waste byproduct of wastewater treatment. The treatment and management system of biosludge represents a second treatment stream that includes several treatment units that take up a considerable part of the wastewater treatment plant and significantly add to its capital and running costs. The re-use of treated biosludge or its disposal affect the treatment techniques chosen to manage it. The optimum management system of biosludge is chosen depending on certain factors including, the type of wastewater generating the biosludge, applicable environmental legislations as well as site and climate conditions. Designing an optimum management system for biosludge generated from plants treating wastewater produced from Gas-To-Liquid (GTL) plants is important in many areas, such as the Gulf area. In cases where the GTL plant is located in an area that has high land value, warm arid climate and no market for sludge re-use, the biosludge management system needs to be optimized for such conditions.

This research consisted of two parts: (i) an experimental investigation of the characteristics of GTL biosludge and its aerobic treatability, and (ii) developing a design model to obtain the optimum design of biosludge management system in general, and GTL biosludge in particular.

Biosludge generated from an existing GTL wastewater treatment plant was investigated. Sludge samples were collected and analyzed for solid content. Lab results characterized the biosludge to have an organic content of more than 80% of its dry solids content, qualifying digestion as an adequate volume reduction and stabilization technique. Aerobic digestion achieved solid content reduction values of as high as 70% in 9 weeks. Results indicate that the decay constant specific to the investigated GTL biosludge is 0.0145day⁻¹.

The developed design model consists of three sub-models: a sizing and design sub-model, a simulation sub-model, and cost and optimization sub-model. The recommended treatment units for GTL biosludge treatment are Aerobic Digestion (AD), Dewatering by Centrifuge and Drying Beds (DB).

The design sub-model is used to size the AD, centrifuge, and DB for selected values of residence times in the AD and DB.

The simulation sub-model is then used to track the daily changes of the water and solids content of the inflow biosludge through the AD, centrifuge and DB accounting for the ambient temperature that varies on a daily basis throughout the year. The mass flux of biosludge with known water to solid content ratio is fed through the line-up. The Aerobic Digester (AD) then reduces the solids content by digesting the organic fraction of its makeup. Biosludge is then discharged from the AD in the same amounts but with higher water content where it is fed into the centrifuge, which is expected to dewater it to reach a preset water content percentage. Finally, the biosludge is sent off to drying beds to dry and lose further water content through drainage and evaporation. Biosludge is then either disposed in landfills or reused in
land application. The simulation-sub-model predicts the daily amounts of final sludge collected from the DB and transported to the landfill (LF) for disposal.

The cost and optimization sub-model generates the alternative designs to be sized by the design sub-model and calculates the capital and operating costs based on the results of the simulation sub-model for each design alternative. Two main design variables are varied to identify the optimum design: residence time in the AD and time of stay in the DB. The minimum cost alternative is chosen as the optimal treatment line-up recommendation. The minimum cost is a trade-off between the cost of biosludge being aerated for a longer time and the drying and disposal cost savings achieved by smaller volumes of produced biosludge.

The model was applied to obtain the optimum management system for 360 ton/day of GTL biosludge under five cases: (i) minimum cost, (ii) with constraint on the daily disposal rate of 20 ton, (iii) potential re-use of processed sludge, (iv) domestic biosludge, and (v) refinery biosludge applications. The optimum design for case (i) did not include the AD as its cost was higher than the reduction in cost of the subsequent treatment units. The design comprised of the centrifuge, drying beds (for 8 days), transportation and disposal to LF. This alternative results in 20.3 tons/day at a unit cost of $7.26/ton. The design for case (ii) ensured a rate of disposed sludge of less than 20 tons/day to meet the EPA requirement hence required an AD with a residence time of 21 days plus 8 days in DB with a unit cost of $9.97/ton. Case (iii) suggested a solution for GTL biosludge to qualify for the land application requirement based on 28 days of residence time in the AD and one day in the drying beds. This would result in 16.9 tons/day at unit cost of $10.69/ton. Cases (iv) and (v) deal with domestic and refinery biosludges that have higher decay constants resulting in a drop in amounts and costs of biosludge produced to 16.8 tons/d of sewage sludge costing $6.01/ton and 10.21 tons/d of refinery sludge costing $4.55/ton. The model gives results on an average of one year but allows the versatility of monitoring seasonal performances and varying the design accordingly.

Conclusions drawn from this research are divided into two parts; those related to the experimental investigation; and those related to the developed model, its usefulness and design directions as shown through the results of the model applications.

Experimental investigations show that the biosludge generated from plants treating wastewater produced from GTL plants has an organic content of more than 80% of its dry solids, which suggests the feasibility of its treatment through digestion techniques whether aerobically or anaerobically. Also it is worth noting that no external bacteria were inoculated to the sludge. Furthermore, the carried out bench scale experiments simulate aerobic digestion showing that reduction in the biosludge solid content achieved through aerobic digestion can be as high as 70% in 9 weeks. Results indicate that the decay constant specific to the investigated GTL biosludge is 0.0145 day\(^{-1}\) at 20 degrees. However, it is important to consider that the experiments did not account for pH or temperature adjustments during the aerobic digestion.
Moving on to the optimization model, the design sub-model can be used for initial sizing and conceptual design of the Aerobic Digester, its aeration system, the centrifuge unit and drying beds. On the other hand, the simulation sub-model can track the solids content, sludge volumetric flow rates, centrate volumes, amount of polymers in the centrifuge, airflow and power requirements for the aeration system as well as drainage water and evaporated water from the drying beds. The estimates can be a good base to predict the capital and operation cost of the various treatment units.

As for the simulation sub-model, it can predict the daily final sludge quantities to be transported and disposed of to the landfill accounting for climate conditions and the features of the design alternative.

The main function of the model lies in the optimization sub-model, which can generate technically feasible alternatives and identify the optimum design that achieves the least unit cost for managing one ton of the inflow sludge under the project specific conditions. It can also recognize the minimum cost design that would meet any environmental constraints such as a limit on maximum disposal rate of the sludge or a minimum degree of stabilization. The cost sub-model gives estimates for the make-up of the capital and operational costs for the sludge management system (material, power, chemicals, AD, centrifuge, DB, transportation and disposal fees).

The optimization sub-model has indicated that the GTL biosludge for the investigated case study can be optimally managed using centrifuge and drying beds without the need for aerobic digesters if design is only based on cost considerations. The low decay constant of the GTL biosludge is the prime cause for increasing the capital and operational cost of the AD stage. If environmental constraints are imposed, the optimization sub-model recognized the need for aerobic digestion and estimated its size. The optimization sub-model has identified a different optimum design for municipal biosludge that has a higher decay rate proving that the AD was an essential part of the management system for this case. For other industrial biosludges with high decay rates, the amounts of produced biosludge and associated unit costs decrease.

Recommendations for future research are suggested to enhance the results of the current research and include, developing an experimental study that investigates the feasibility of anaerobic digestion of the GTL biosludge. Also, a more detailed simulation model can be useful to estimate the DO uptake by the volatile organic matter in the aerobic digester. A better estimate of the required airflow under all operating conditions shall improve on the cost estimate of power by the air blowers. Furthermore, a more detailed simulation can be useful in tracking the changes in moisture content of the sludge cake in the drying beds, either by free drainage or evaporation as well as study the effectiveness of sludge movement from one bed to another. Finally, a more detailed simulation sub-model that tracks the variations in volatile solids content of the biosludge as it flows from one treatment unit to another allowing for the use of the decay constant derived for volatile suspended solids, would allow for more accurate results.
Works Cited


[10] Rana A. Mostafa, Interview with Technical WWTP Team at Pearl GTL, April 2013.


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