Life-Cycle Assessment of Wastewater Treatment Plants

by

Bo Dong

Bachelor of Engineering, Environmental Engineering
Nanyang Technological University, 2011

Submitted to the

Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering
in Civil and Environmental Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2012

Signature of Author..
Department of Civil and Environmental Engineering
May 18, 2012

Certified by..................................
Eric E. Adams
Senior Research Engineer and Lecturer of
Civil and Environmental Engineering
Thesis Supervisor

Accepted by..............................
Heidi M. Nepf
Chair, Departmental Committee for Graduate Students

Life-Cycle Assessment of Wastewater Treatment Plants

by

Bo Dong

Submitted to the Department of Civil and Environmental Engineering on May 18, 2012
in Partial Fulfillment of the Requirements for the Degree of
Master of Engineering in Civil and Environmental Engineering

Abstract

This thesis presents a general model for the carbon footprints analysis of wastewater treatment plants (WWTPs), using a life cycle assessment (LCA) approach. In previous research, the issue of global warming is often related to traditional industries with high carbon dioxide (CO_2) emissions, such as power plants and transportation. However, the analyses of wastewater treatment plants (WWTPs) have drawn increasing attention, due to the intensive greenhouse gas emissions (GHG) from WWTPs. WWTPs have been listed in the 7th place for both methane (CH_4) and nitrous oxide (N_2O) total emissions. In addition, WWTPs indirectly contribute to a huge amount of CO_2 emissions.

The final results have shown that more than half of the carbon footprints from the La Gavia WWTP are from the indirect emissions of CO_2, which is caused by the intensive energy consumption. The direct emissions of CH_4 and N_2O combined contribute more than 30 percent of GHG emission. The finally section of the thesis compares the environmental impacts of the La Gavia WWTP with case of no WWTP at all. It has been concluded that although the La Gavia WWTP increased the total carbon footprints, it has much better control of eutrophication potential (EP).

Thesis Supervisor: Eric Adams

Title: Senior Research Engineer and Lecturer of Civil and Environmental Engineering

ACKNOWLEDGEMENT

I would like to thank everyone who has helped me or encouraged me during my study in the M.Eng program. This thesis would not have been possible without your support.

First of all, I would like to express my deepest appreciation to my parents. Thank you for your continuous encouragement and financial support. Without you, I wouldn't make through those tough days.

I want to thank my supervisor, Dr. Eric Adams, for giving me patient guidance and valuable advice during the entire project.

I want to thank my fellow M.Eng classmates, who made my life at MIT more unforgettable. You are amazing. Special thanks for my Spain team members, Xin Xu and Jong Lim. Our LDX Environmental is the best.

I want to thank Dr. Pete Shanahan, Dr. Windsor Sung, and Angela Schindler for giving me continuous support for the project.

Last but not least, I would like to thank Emma Montes Parra and Gloria Garralon Lafuente from Cadagua S.A. for allowing us to visit Spain.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. Background

Global climate change, also known as global warming, is caused by the atmospheric build-up of greenhouse gas. The increased concentration of greenhouse gas in the atmosphere directly leads to global temperature rise, which in turn causes sea level rise, flooding, and extreme weather. The three major greenhouse gases are generally considered as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O, also known as laughing gas). CO_2 is no doubt the largest amount of all greenhouse gases, followed by CH_4, which has a 21 times greater global warming potential (GWP) than CO_2. Although N_2O is the least abundant among these three gases, contributing up to 4.5 percent of total GHG emissions (USEPA, 2011), the high GWP (310 CO_2-eq.) of N_2O has drawn increasing attention.

While people have focused on CO_2 emissions from construction, transportation and power generation, wastewater treatment plants (WWTPs) also play a significant role. USEPA (2011) have listed WWTPs as the 7th largest contributors to both CH_4 and nitrous N_2O emissions. Therefore, in order to reduce GHG emissions, more and more regulators worldwide began to require and enforce mandatory reports and measurements on GHG emissions from WWTPs.

A typical WWTP consists of a series of unit processes including primary treatment, biological secondary treatment, occasional tertiary treatment and sludge treatment. There are multiple sources of GHG emissions (direct and indirect) from WWTPs. The major source of CO_2 emission associated with WWTPs is from electricity consumed to operate different treatment processes. CO_2 is also a product of aerobic digestion in biological secondary treatment. CH_4 is a typical product of anaerobic digestion employed in some forms of secondary treatment and in sludge digestion. N_2O is the intermediate product resulting from incomplete reactions in the biological nutrient removal process. Among the three GHGs, there is great uncertainty about the amount of N_2O

To properly account for all these emissions over the entire lifetime of a WWTP, a life cycle assessment (LCA) is often conducted. There are various commercial LCA packages on the market; and the GaBi 5 developed by PE International was used in this project.

1.2. Project Description

This project is sponsored by Cadagua S.A., a water and wastewater utility company in Spain seeking sustainable development and commitment to environmental regulations. In order to better understand the real contributions to global warming from wastewater treatment plants in Spain. It has been requested to evaluate the GHG emissions from WWTPs, investigate potential methods to reduce such gas emissions, and identify the N_2O emission in particular.

In response to Cadagua's request, LDX Environmental formed a team of three members from MIT's Department of Civil and Environmental Engineering's Master of Engineering Program: Bo Dong, Xin Xu and Jong Hyun Lim. The three students visited Spain during January 2012. Based on the visit, the La Gavia WWTP in Madrid was selected as the plant of interest, due to the data availability and the advanced treatment processes.

1.3. Objectives

Previous studies quantified various emissions from WWTPs, but they are either on the laboratory-scale or site specific. Hence, these studies cannot be applied to any WWTP in Spain. Therefore, the primary goal of this project was to quantify the contribution of WWTPs to global climate change and to estimate the amount of emissions from each individual process within WWTPs.

2. LITERATURE REVIEW

2.1. Green House Gas (GHG)

2.1.1. Emission Sources

The three major greenhouse gases are generally considered as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The estimation of the amount of greenhouse gas emissions can be made by several methods. For example, Figure 2.1 shows the total greenhouse gas emissions by types of greenhouse gases, while Figure 2.2 shows emissions estimated by sectors.

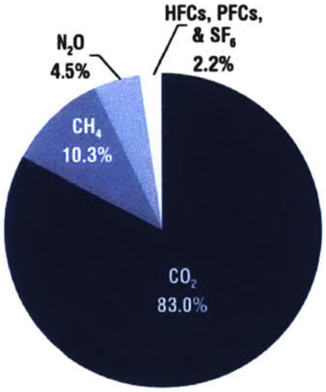


Figure 2.1 Greenhouse Gas Emissions by Types of GHG (USEPA, 2011)

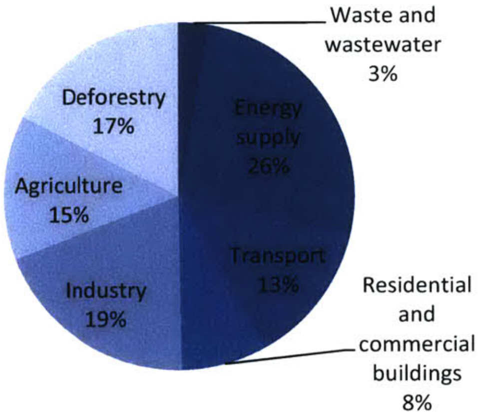


Figure 2.2 Global Anthropogenic Greenhouse Gas Emissions in 2004 (IPCC, 2007)

2.1.2. Global Warming Potential (GWP)

The concept of global warming potential (GWP) is defined as the ratio of the radioactive forcing of an instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas (IPCC 2001). The reference gas used here is CO_2, with the unit of carbon dioxide equivalent (CO_2-Eq). Moreover, difference gases have different residence times in the atmosphere. The GWP is normally reported on a 100-year basis. For example, CO_2 itself has a GWP of 1 CO_2-Eq on a 100-year basis. The GWP of CH_4 is 21 times more powerful than that of CO_2. Hence, the GWP of CH_4 is 21 CO_2-Eq. Similarly, the GWP of N_2O is 310 CO_2-Eq. Table 2.1 shows the GWP of the three major greenhouse gases.

Table 2.1 Global Warming Potential of CO_2, CH_4 and N_2O (USEPA, 2011)

Gas	**GWP (CO_2-Eq) (100 year)**
CO_2	1
CH_4	21
N_2O	310

The term carbon footprint is, defined as the sum of all greenhouse gas emissions and expressed as global warming potential (GWP) in the units of kg CO_2-Eq.

2.1.3. Direct Emissions

Under the concept of LCA, various emissions to the environment can be further grouped into two categories – direct emissions and indirect emissions. Direct emission is easy to visualize. It includes emissions within the treatment plant, such as non-biogenic carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). These gases come from both stationary sources, like biological treatment processes, and mobile combustion sources, like cars and trucks. The CO_2 emission from secondary biological treatment process should not be counted as direct emission, due to its biogenic source. Section 2.1.5 provides a detailed discussion of CO_2.

2.1.4. Indirect Emissions

Different from direct emissions, indirect emissions refer to emissions outside plants. However, these emissions are directly caused by the product or process studied. Indirect emissions may include emissions from the electricity purchased from power plants, during transportation and from the production of chemicals. Past researches (Knosby et. al, 2010) have demonstrated that indirect emissions could contribute more than 60 percent of the total greenhouse gas emissions in WWTPs.

Biosolids, as the final product of the sludge treatment, need to be carefully studied in terms of indirect GHG emissions. The transportation of waste biosolids is an important source of emissions due to fossil fuel combustion. Moreover, the ultimate disposal of biosolids can also be a source of fugitive N_2O and CH_4 emissions, especially when waste is placed in landfills or used for composting and agriculture applications.

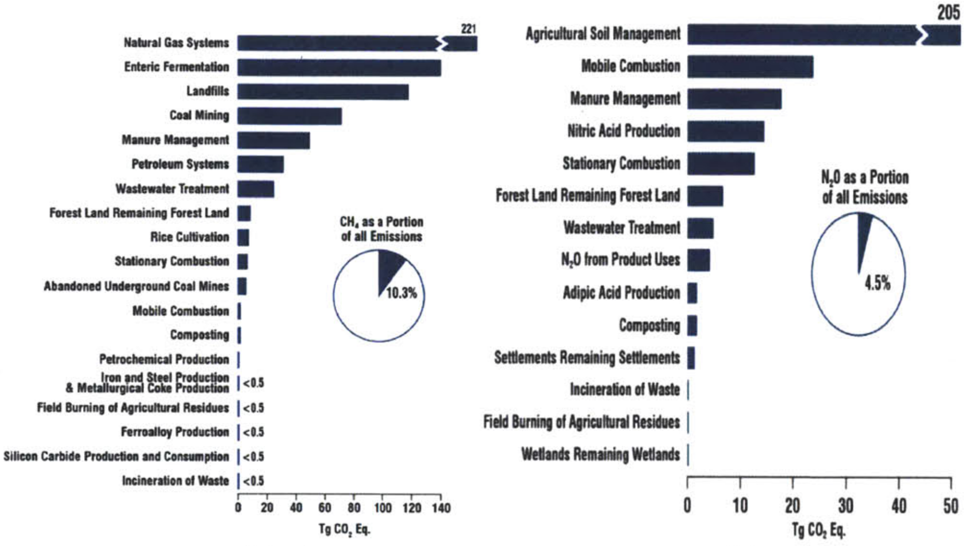
2.1.5. Carbon Dioxide

As shown in Figure 2.1, carbon dioxide (CO_2) contributes to more than 80 percent of total greenhouse gas emissions. It is also the largest contributor to the carbon footprints of WWTPs. Emissions from both direct sources and indirect sources add up to total CO_2 emission.

Some CO_2 comes from the secondary biological treatment process as a result of respiration of organic matter (BOD). However, this amount of carbon dioxide is often neglected from greenhouse gas accounting due to its biogenic origins (USEPA, 2006). Tillman el al. (1998) adopted a similar approach in the LCA case study of municipal wastewater systems, meaning that the biogenic CO_2 is excluded from greenhouse gas emission from WWTPs.

2.1.6. Methane

According to USEPA (2011), CH_4 results in ten percent of the total greenhouse gas emissions. Figure 2.3(a) shows that WWTPs are the seventh largest sectors that contribute to methane emissions.



(a) (b)

Figure 2.3 (a) Methane Emissions by Sectors and (b) Nitrous Oxide Emissions by Sectors (USEPA, 2011)

Methane (CH_4) can be released throughout the systems where anaerobic conditions exist. Most of the CH_4 emissions come from open anaerobic reactors, lagoons and the sludge handling processes. Limited amounts of CH_4 can also be emitted from aerobic processes when it is poorly managed. In real practice, CH_4 can be neutralized if burned (flared or employing other forms of combustion). Energy, as a byproduct from this neutralization process, can be in turn used to heat the anaerobic digester. Inefficiencies in the CH_4 gas collection systems combined with the incomplete combustion of the digester gases can still result in CH_4 emissions.

2.1.7. Nitrous Oxide

As Figure 2.3(b) shows, nitrous oxide results in 4.5 percent of the total greenhouse gas emissions, which are often overlooked due to the relatively small amount in the atmosphere. It is still a fact that WWTP is ranked the 7th place in nitrous oxide emissions by sectors.

Nitrous oxide (N_2O) can be generated from a WWTP with a biological nutrient removal process, which is designed to reduce the concentration of total nitrogen in the treated wastewater. N_2O is normally considered as a byproduct of the nitrification process and an intermediate product of the denitrification process. The amount of N_2O released depends on the operational conditions of the biological nutrient removal processes. In addition, N_2O emission can be found in the receiving water, where treated effluent is discharged.

Although there is a lack of reference for a good estimation of nitrous oxide emissions from WWTPs, the fact is that the N_2O emission is bound to increase significantly as stringent effluent nitrogen controls come into force. However, if the biological nutrient removal process is not adopted and excess ammonia continues to pollute the waterways, there would be less N_2O emission to the atmosphere and thus lower global warming potential. Another environment impact of receiving water would inevitably arise, i.e. eutrophication, which would result in excessive plant growth and depletion of oxygen in the water. This impact is of greater concern for wastewater treatment plants whose effluents are discharged directly into small rivers or lakes than those into the oceans. This trade-off between the global warming potential and the eutrophication potential produces a challenge: how to reduce greenhouse gas emissions and at the same time minimize the ecological effects caused by eutrophication.

2.2 Life Cycle Assessment (LCA)

2.2.1 Concept of LCA

Life Cycle Assessment (LCA) is a tool that is used to evaluate the potential environmental impacts of a product, a process or a service. LCA is also the synonym for 'Life Cycle Analysis' or 'Cradle-to-grave Analysis' (Crawford, 2011). As the name 'cradle-to-grave' suggests, LCA involves the assessment of the entire life cycle of the product, from the preparation of raw materials, through the manufacture of the product to the disposal of waste. LCA provides both a holistic picture of a product's environment impacts and comparisons between stages of product life.

LCA Application to WWTPs

As a technical approach, LCA has been applied to WWTPs since the late 1990s. The links between the environmental impacts and treatment process are the relevant inputs and outputs of the product system (Crawford, 2011). The inputs normally include raw materials and energy. However, outputs may vary widely, including products, emissions to air, emissions to water, solid wastes and other byproducts. As in the case of wastewater treatment plants, the major inputs are wastewater from sewage collection systems, electricity used for pumping and mixing, and other chemicals added. In contrast, outputs include treated effluent to the receiving water, sludge and various gas emissions.

There are several different ways to assess the environmental impact of WWTPs under the concept of LCA. According to Emmerson et al. (1995), the life cycle of WWTPs generally involves the construction phase of WWTPs, production of wastewater phase (or use phase) and the final demolition phase. They also pointed out that both the construction phase and demolition phase have only a trivial impact on the environment within the life cycle of the plant. Later research focuses more on the operational phase. Tillman et al. (1998) have studied alternatives for WWTPs in Sweden using the LCA approach. Lassaux et al. (2007) conducted case study on the anthropogenic water cycle (''from the pumping station to the wastewater treatment plant''). Other analyses of this increasingly popular topic also include the comparison of environmental impacts between different WWTPs (Hispido et al., 2008), the comparison between different LCA methods for WWTPs, and the assessment of WWTPs with seasonal variations (Hospido, 2004).

As explained in Section 2.1, both direct emissions and indirect emissions are counted as anthropogenic greenhouse gas emissions. Therefore, in the LCA application to WWTPs, both emission sources should be considered.

2.2.2 The LCA Framework

A life cycle assessment is a complex process that involves several different stages. The International Organization for Standardization (ISO) has standardized a framework for LCA. According to the most updated ISO 14040:2006, LCA contains four phases:

- goal and scope definition
- inventory analysis
- impact assessment
- interpretation

The relationship between the different phases is shown in Figure 2.4. The Goal and scope definition, inventory analysis and impact assessment are performed in sequence, while interpretation occurs throughout the processes.

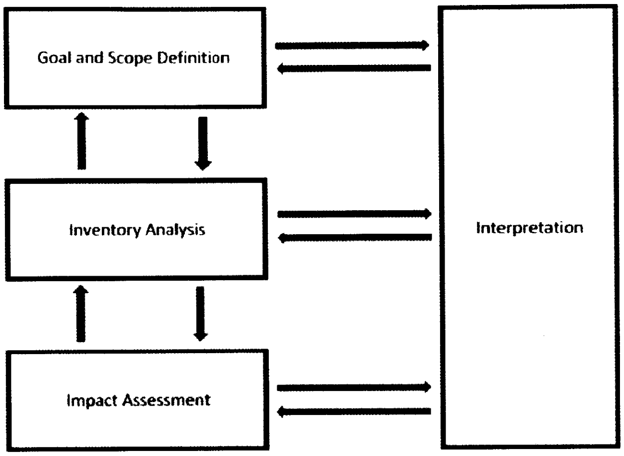


Figure 2.4 Four Phases of LCA (ISO14040:2006)

2.2.3 Goal and Scope Definition

Defining the goal and scope are in the first stage of LCA. The goal statement of an LCA application defines the purpose of the study. It includes some or all of the following elements: reasons for the study, type of approach, targeted audience and use of final results. The scope definition normally explains which stage of the product life cycle and what boundaries are considered. ISO 14040:2006 lists twelve items for scope definition, including:

- the product system to be studied
- the functions of the product/system
- functional unit
- impact category selected and methodology of impact assessment and interpretation to be used
- initial data requirement and quality
- assumptions
- limitations

- types of critical review, if any

Scope definition is an important step that defines the breadth, depth and details of the study.

Functional Unit

The definition of functional unit is the first key step in goal definition. A product system normally has several functions that represent different fates of raw materials. The functional unit defines both the type and quantification of the selected product function. It is used as a reference unit and enables the quantitative analyses between inputs and outputs. The concept of functional unit becomes particularly critical when the performances of different product systems are studied. The same functional units allow meaningful comparisons on a common basis. For example, a functional unit could be a ton of concrete or a vehicle seating five passengers.

In wastewater treatment literature, functional units are chosen based on different purposes of study. According to Suh and Roisseacux (2001), it is better to adopt flow rate (volume of wastewater treated within a certain period of time) as the functional unit, because it is clear and easy to establish inventory. Hospido et al. (2008) choose person equivalent as the functional unit for the comparison between different plants. Lassaux el al. (2007) used one cubic meter of water at consumer tap. However, under certain circumstances, some functional units are interchangeable through a scaling factor. For example, a WWTP has a capacity of treating $10,000m^3/d$. We can set functional units either as $10,000m^3/d$ or $1\ m^3$. Therefore, the final results will have a ten-thousand-time difference.

Although a functional unit could be a very small volume or a flow rate in a short time period, it should represent the long-term averaged performance of a WWTP. Details of data collection and quality are discussed in Section 4.1.1.

System Boundaries

In general, a product system consists of several unit processes; and each unit process could have one or more inputs and outputs. Therefore, the system boundary defines which unit processes to include and, hence, which inputs and outputs to include. The system boundary may also be affected by the access to data, relative assumptions, project budget and other constraints. According to ISO14040:2006, some processes, inputs and outputs have only minor effects on the final results, and can be excluded from the system boundary.

By the definition from Sonnemann et al. (2004), LCA can be focused on either the life-cycle time boundaries of WWTPs (i.e., construction phase, operational phase and demolition phase) or the geographical boundaries of the anthropogenic water cycle.

Based on the discussion of time boundaries, Lundie el al. (2004) and Lassaux et al. (2006) have demonstrated that the environmental impacts of the construction phase are much smaller than those of the operational phase. The reasonable assumption for the demolition phase is that its environmental impact is smaller than those of the operational phases and construction phases.

From the geographical point of view, conventional municipal WWTPs often include primary treatment, secondary treatment and sludge treatment. These basic processes should be included in the LCA, due to their important impacts on the environment. The availability of other treatment processes, such as tertiary treatment, nutrient removal and disinfection, differ from plant to plant. However, these plant-based processes should be carefully considered, due to their different impacts on the final results.

2.2.4 Inventory Analysis

Life Cycle Inventory (LCI) Analysis, the second phase of LCA, involves data collection and processing and allocation of resources. Sonnenmann et al. (2004) summarized a four-step methodology in inventory analysis. These steps are:

- data collection
- normalization
- allocation
- data evaluation

However, the literatures report the use of slightly different methodologies. For example, ISO14040 standard includes normalization in the life cycle impact assessment phase. The data evaluation step is not unique in Life Cycle Impact Assessment (LCIA). Instead, data should be evaluated throughout the entire LCA.

Data collection

Once the system boundary is well defined, data can be collected according to the inputs and outputs of each unit process. Figure 2.5 describes a generic overview of data collection regarding the system boundary. Similar approaches also apply to the individual unit process data collection. In some analyses, data collection could involve intensive labor, time and money.

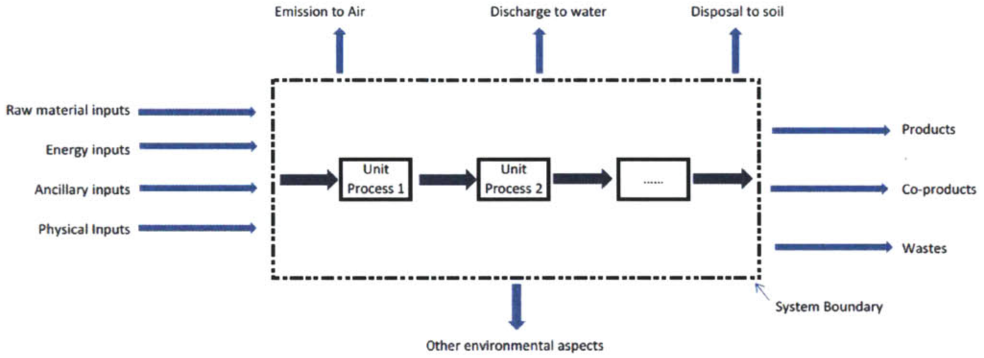


Figure 2.5 Generic Data Collection

Raw data needs to be further processed before the final life cycle inventory. In addition, the initial data quality must be checked with the following requirements (Sonnemann, 2004):

- time-related coverage
- geographical coverage
- technology coverage

These requirements guarantees the final LCA results are valid over a relative long time scale, a wide range of geological locations and a variety of technology mixes.

For the LCA of a WWTP, data is gathered mainly from the daily plant operation. The flow rate varies between seasons and even years. An adequate time frame (e.g. five years) is necessary to eliminate seasonal and meteorological variances. Geographical coverage depends on the goal and scope of study. For a single plant analysis, only local information should be used. Technology coverage reflects the types of technology used, whether a single operation or a technology mix. The wastewater treatment processes could have various treatment technologies for a single stage. For example, sludge digested gas can be ignited, recycled or a mix of both.

Normalization

As discussed in Section2.2.4, raw data need to be further processed before allocation. This step is called normalization in some of the literature. Raw data needs to be normalized according to the functional unit defined in the goal and scope phase. For example, in WWTP, if flow rate is used as the functional unit, all other raw data collected should be recalculated based on this flow rate.

Allocation

Allocation means the distribution of resources, wastes and emission for each single unit process to relative environmental impacts. The functional unit is the key that connects inputs and outputs and connects unit processes.

2.2.5 Impact Assessment

The main purpose of Impact Assessment is to translate the results from inventory analysis to a more understandable and precise interpretation of the environmental impacts of a product system. Despite the requirements for LCI, the three mandatory elements for impact analysis are

- selection and definition of impact categories
- classification
- characterization

Selection and Definition of Impact Categories

The selection and definition is closely related to the goal of the LCA study. Different impact categories may include global warming, eutrophication, human toxicity, and ozone depletion. The results from inventory analysis can then be assigned to the respective impact categories.

Classification

Continued from the impact categories selection step, this step is to assign the LCI results into different environmental impacts. However, it becomes confusing when two or more flows have the same impacts. A characterization factor is defined for each impact category. For example, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) all have impacts on global warming, but their relative contributions to global warming are different. Therefore, global warming potential (GWP) is used as the characterization factor, with the unit of CO_2 equivalent (CO_2-Eq). From IPCC report, the GWP for CH_4 is 21 CO_2-Eq. Similarly, the GWP for N_2O is 310 CO_2-Eq.

Characterization

Characterization refers to the calculation of category indicator results. The results from LCI are calculated using the common factors defined in classification. This step can be achieved in various ways, for example using matrices. Computer software can also be used to assist in calculations.

2.3 Cadagua and the La Gavia WWTP

2.3.1. Company Profile

Cadagua, S.A., the sponsor of this project and one of the Ferrovial's subsidiaries, is a well-recognized Spanish company. It is a leading force in the field of engineering and construction of water purification and treatment plants.

Founded in 1971 and with 40 years' experience, Cadagua has been very active in the development of water treatment and desalination. It has successfully designed and built more than 200 water treatment plants all over the world (drinking water, wastewater, and desalination installations, as well as industrial facilities), achieving a total treatment capacity of over 14,500,000 m^3/d. Over 17,000,000 inhabitants benefit from the company's operation and maintenance services. Figure 2.6 is a chart showing Cadagua's main service areas and installed treatment capacity (Cadagua, 2011)

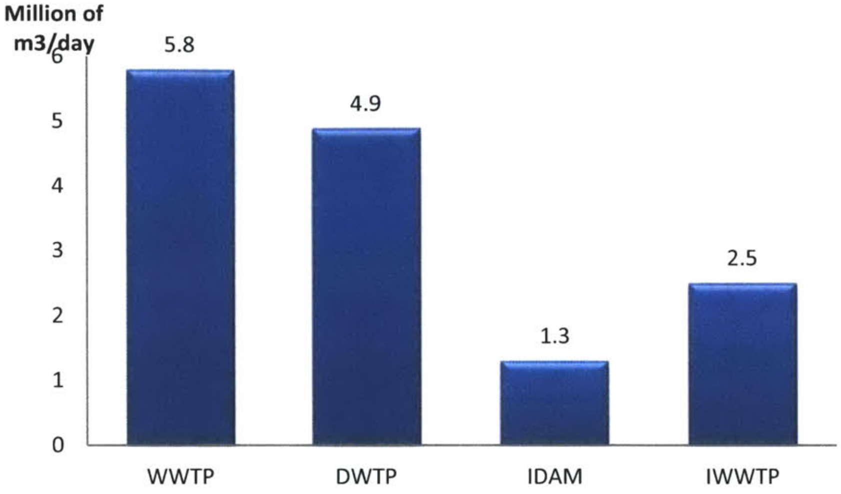


Figure 2.6 Treatment Capacity of Cadagua

Research, Development and Innovation (R&D&i) Department in Cadagua aims at providing better measure-made solutions for each of the installations, in order to improve global efficiency and lower operation and maintenance costs. Recent Cadagua projects include process study to minimize sludge production, nutrients recovery and optimization of power consumption in treatment plants. The project *Assessment of the Carbon Footprint in Wastewater Treatment Plants and Sustainability Analysis for Process Selection* is also one of the ongoing projects, with collaboration with our consulting group LDX Environmental at MIT.

Four WWTPs were visited by our team in January 2012: La Gavia and Boadilla near Madrid, and Ribadesella and Villapérez near Oviedo, Spain. While all four WWTPs were visited data was only collected, and potential measurements are only considered for the La Gavia and Boadilla WWTPs.

Since all four WWTPs employed similar treatment processes, a comprehensive life cycle assessment is carried out on La Gavia WWTP based on the data acquired from Cadagua. The GaBi 5 software is used to assist the LCA. Later, the LCA on Boadilla WWTP will be conducted in a similar manner.

2.3.2. The La Gavia WWTP

Inaugurated in June of 2005, the La Gavia WWTP is located in the district of Villa de Vallecas, southeastern Madrid. The plant resides on the left bank of the Manzanares River and it treats sewage from the La Gavia I and II sewer mains as well as the surplus from the La China WWTP. Figure 2.7 is a plane view of the La Gavia WWTP, and Figure 2.8 depicts the treatment plant's service areas (encompassed by red line).

Figure 2.7 The La Gavia WWTP Plan View

(http://www.acciona.com.au/press/photoGallery/index.php/Water/Waste%20Water%20Treatment%20Plants/)

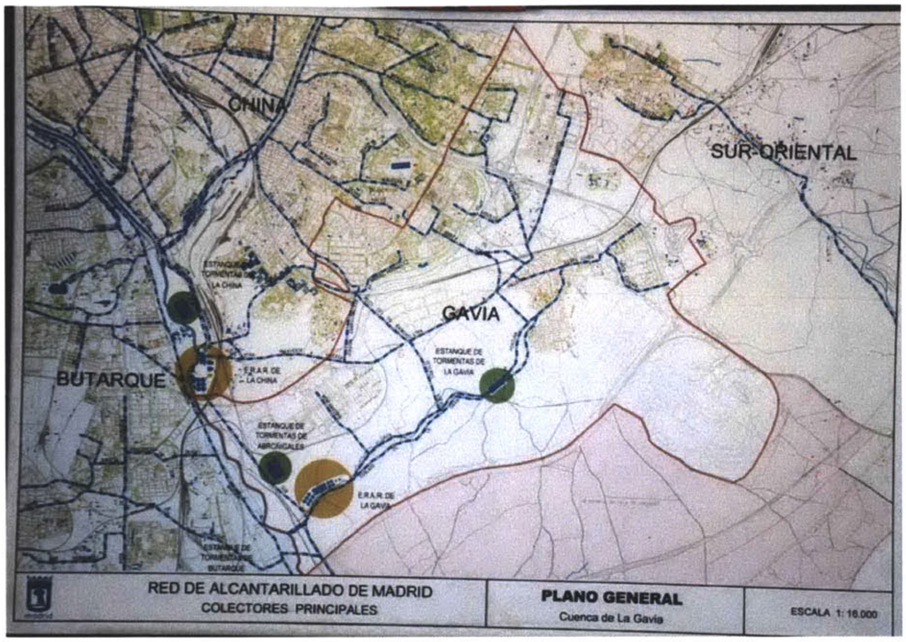


Figure 2.8 The La Gavia WWTP Service Areas

The La Gavia WWTP treats wastewater from about a million people (residential and industrial) and has a design capacity of 2m^3/s average flow. Using advanced biological treatment processes incorporated with nutrient removal, La Gavia WWTP is able to eliminate 97% of organic matter and suspended solids and about 85% of total nitrogen and total phosphorous from the wastewater (Table 2.1), thus meeting the strictest sewage treatment standards. The plant is also in line with the National Sewerage and Wastewater Treatment Plan (1995-2005), which was enforced by the Ministry of the Environment in Spain to improve the water quality in the Manzanares River.

Table 2.1 Removal Efficiency at the La Gavia WWTP

	Influent	**Effluent**	**Percentage Removal**
Units	mg/L	mg/L	%
BOD	350	12	97
SS	340	12	96
Total N	62	10	84
Total P	8	1	87

In addition, the plant is designed to allocate approximately 10% of the treated water to watering green areas using a tertiary treatment process. This is part of the Madrid Water Re-Use Plan, a large-scale strategy to use recycled water for park irrigation and street cleaning services.

Treatment Processes

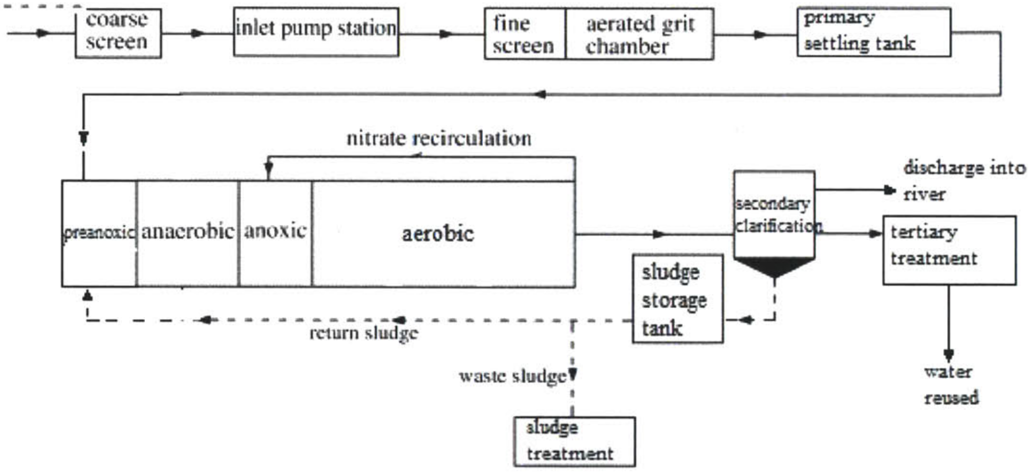


Figure 2.9 Schematic Diagram of Treatment Processes at the La Gavia WWTP

Figure 2.9 shows the simplified schematic of each treatment process employed in the La Gavia WWTP. Basically, the plant consists of two lines, wastewater line and residual sludge line (Figure 2.9 shows mostly the water line). There are typically four stages associated with wastewater treatment processes: pretreatment, primary, secondary and tertiary treatment respectively. In case of high flow rate, certain amount of wastewater is bypassed after the primary treatment. Some of the functions and design parameters of each stage will be discussed in details as follows.

1) Pretreatment

At the entrance of the plant, wastewater is loaded with a large volume of solids that must be removed so that they won't obstruct the pumps and machinery in further treatments. This stage is called pretreatment, which can be divided into several parts.

Coarse/wide screens (see Figure 2.10 a) separate large solids. They consist of a deep tank, located at the inlet to the treatment plant, where the walls are angled to facilitate the descent of the solids and the sands decanted to a specific area. This treatment typically removes materials larger than 10 cm.

Fine screens (see Figure 2.10 b) are installed after wide screens. Water passes through a gate that prevents materials (normally of a size greater than 6 cm) from passing by. The bars must be purged continuously, or they will become blocked. This is achieved by means of automatic movable elements that are driven by chains or curved grids with rotating combs.

(a) (b)

Figure 2.10 (a) Coarse Screen and (b) Fine Screen

Aerated grit chamber (Figure 2.11) is where grit is removed by aerating and stirring the water with a blower which causes the grit to settle down to the bottom of the chamber while keeping lighter organic matters in suspension to be processed further downstream. The lightest grease on the water surface is then skimmed out with combs.

Figure 2.11 Aerated Grit Chamber

Most waste generated in the pretreatment (sand, grease and large solids) are compacted and collected in containers. Finally, they are sent to sludge treatment processes or directly to landfills.

2) Primary Treatment

Primary treatment usually refers to primary settling tanks or primary clarifiers. It is designed to remove both organic and inorganic solids by the physical process of sedimentation. There are 6 circular primary tanks in the La Gavia WWTP, which allow water to stand for 1.43 hours. Approximately 40 to 60 percent of the total suspended solids are removed from the wastewater. The remaining solids, either in suspension or dissolved, are usually be biologically treated in subsequent processes. The primary sludge is the debris that settles at the bottom of the tanks.

3) Secondary Treatment

Secondary treatment in the La Gavia WWTP is an advanced biological activated sludge nutrient removal reactor (BNR). It contains four zones connected in series (preanoxic-anaerobic-anoxic-aerobic). Each zone plays a different role in the removal of nutrients. There are totally 6 parallel reactors, with a total volume of 100,800 m^3, and the total retention time of 14 hours.

The preanoxic zone is designed for denitrification and the enhanced growth of phosphorus-accumulating microorganisms. The activated sludge from the secondary clarifier is pumped back to this zone (external recycle). In the absence of dissolved oxygen, bacteria utilize BOD in the influent, reducing the nitrates to gaseous nitrogen, thus alleviating the nitrate loading from the return sludge in the subsequent anaerobic zone.

Wastewater treated by the preanoxic zone is then introduced to the anaerobic tank (shown in Figure 2.12a) in which phosphorous release reactions by microorganisms occur under anaerobic conditions.

In the anoxic zone, wastewater is mixed with the nitrified mixed liquor recycled from the aerobic zone (internal recycling). The recycle rate is 300% of the influent flow. This is the zone where the denitrification occurs, and where N_2O is released to the atmsphere. (Sedlak, 1991)

In the aerobic zone (Figure 2.12 b), nitrification takes place where ammonia is reduced to nitrate and nitrite, and luxury uptake of phosphorous also occur. The aerobic zone also facilitates the growth of bacteria that feeds on organic matters. In order to assimilate organic matters, these microorganisms require a significant amount of oxygen, which is added through 12,420 submerged membrane diffusers at the bottom of the aerobic tanks. The air added to the water has been condensed to improve the efficiency.

(a) (b)

Figure 2.12 Secondary Treatment process: (a) Anaerobic Zone (b) Aerobic Zone

4) Tertiary Treatment

The design of the La Gavia WWTP initially contemplated the incorporation of a water reuse system in response to the objectives set by the Madrid Water Re-Use Plan. Therefore, new tertiary treatment was built which employed a system of microfiltration (MF) and ultraviolet (UV) disinfection (shown in Figure 2.13). The designed flow rate is 21,600m3/day, which is to be doubled in a future enlargement. This project will ultimately make it possible to reutilize 25% of the purified water from the WWTP currently in operation. At this time, about 10% of the purified water is treated for reuse. (Hernanz, 2007)

Figure 2.13 Tertiary Treatment: Filtration Tanks and UV Disinfection

5) Sludge treatment

Both primary and secondary processes generate sludge, which consists of mostly water (approximately 97%) and solids. Therefore, before further treated biologically, sludge is thickened to reduce mass and volume by the partial removal of water. In the La Gavia WWTP, two types of thickening are employed: gravitational thickener for primary sludge and centrifugal thickeners for secondary sludge.

After passing through the thickener, the sludge is taken to anaerobic digesters. Anaerobic digestion is a biological process that allows a significant decomposition of organic matter through fermentation in the absence of air. Greenhouse gases, particularly methane and carbon dioxide, are produced during this process.

The sludge must be contained within the digesters at a suitable temperature (about 35 °C). External sources of heat are required in cold seasons. In the La Gavia, part of the digester gas is used as feed for cogeneration, providing heat for digestion in return. The excess biogas is then stored in a storage tank called a gasholder (shown in Figure 2.14) and superfluous gas is burned and released into the atmosphere.

Figure 2.14 Gasholder for Biogas Produced from Sludge Digesters

Up to this point of the treatment of sludge, the reduction of water is minimal, which means the sludge still has a large volume. Dehydration is responsible for eliminating, in large part, the water in the sludge. There are four centrifuges serving for this purpose in the La Gavia plant. After this process, the outgoing sludge contains about 75% water, and is transported to another thermal drying plant for further treatment.

One thing that should be mentioned about the sludge treatment at the La Gavia WWTP is cogeneration, which is the simultaneous production of electricity and utilization of heat. There are 3 motor generators (Figure 2.15 shows two of them) in the plant, producing more than 7,000,000 kWh of electricity every year.

Figure 2.15 Motor Generators

3. METHODOLOGY

3.1. Goal

In response to the request for carbon footprint analysis by Cadagua S.A., the purpose of the life cycle assessment (LCA) is to study the potential environmental impacts of the La Gavia wastewater treatment plant (WWTP), based on the data provided by Cadagua. Particularly, the global warming potential (GWP) and the eutrophication potential are two key impacts of interest. The scenario of no treatment plant will be compared with the results from the La Gavia WWTP.

The target audiences of this study are Cadagua S.A., MIT department of Civil and Environmental Engineering, LCA practitioners and scientists, and the general public. The experts from Cadagua S.A. could use the results from this study to improve the treatment processes in La Gavia WWTP, regarding carbon footprints. Other experts can also apply the model proposed in this study to other treatment plants with similar processes.

3.2. Scope

The scope definition normally explains which stage of the product life cycle and what boundaries are to be considered.

3.2.1. The La Gavia WWTP System

The La Gavia WWTP has collectively five treatment processes: pretreatment, primary treatment, secondary treatment, tertiary treatment and sludge treatment. The functions of each treatment have been carefully studies in Section 2.3.2.

3.2.2. Functional Unit

Flow rate is used as the functional unit for this study. It is defined as 76040 cubic meter per day (m^3/d) of wastewater at the inlet point of the WWTP. This number is the daily averaged flow rate of the La Gavia WWTP. However the functional unit can also be converted to 1 cubic meter of wastewater treated by a scaling factor of 1/76040.

3.2.3. System Boundaries

Time boundary

The three phases of the La Gavia WWTP have been defined as the construction phase, the operational (use) phase and the demolition (end-of-life) phase. During the life cycle of a WWTP, the operational phase has the dominant impact of all phases. In addition, access to the data for the construction and demolition phases is limited. Therefore, within the scope of this project, only the operational (use) phase will be included.

Spatial Boundary

Within the operational phase of the La Gavia WWTP, all of the five treatment processes should be included. However, ISO 14040:2006 also suggests that resources need not be expended on the quantification of processes that will not cause significant change in the final outcome. Based on the operational data given by Cadagua S.A., the operation of tertiary treatment is season-dependent. On a yearly average, it handles only about 0.5 percent of the total wastewater inflow (400m^3/day out of 75300m^3/day). Hence, tertiary treatment was not discussed in this study. Similarly, we are omitting analysis of the bypass flow after the primary treatment process, which happened only twice in year 2011 (Oct 20th and Oct 23rd). The bypassed flow rate is less than 0.1 percent (71m^3/day out of 75000m^3/day).

Figure 3.1 shows the system boundary of the LCA study of the La Gavia WWTP. The five processes are primary treatment, secondary treatment, sludge collection, anaerobic digestion and thermal drying. For simplicity, the pumping, pretreatment and primary treatment processes have been combined into one single process. The blue arrows represent the water line, while the brown arrows stand for the sludge line. The dash-line box is the system boundary. Figure 3.1 does not represent all the environmental flows that go in or out of the system. Other inputs and outputs include electricity, chemicals and gas emissions.

As shown in Figure 3.1, wastewater is introduced from the sewer system to primary treatment. It is further treated in the biological secondary treatment process with nutrient

(N and P) removal. Finally, the secondary effluent is discharged into the receiving water. The impact of the WWTP in the river has been included.

For the sludge line, the primary and secondary sludge are combined in the sludge collection process. The sludge is further treated in the anaerobic digestion and the thermal drying processes. The dried sludge, either sent to landfills or used as fertilizer, is not discussed in this LCA report.

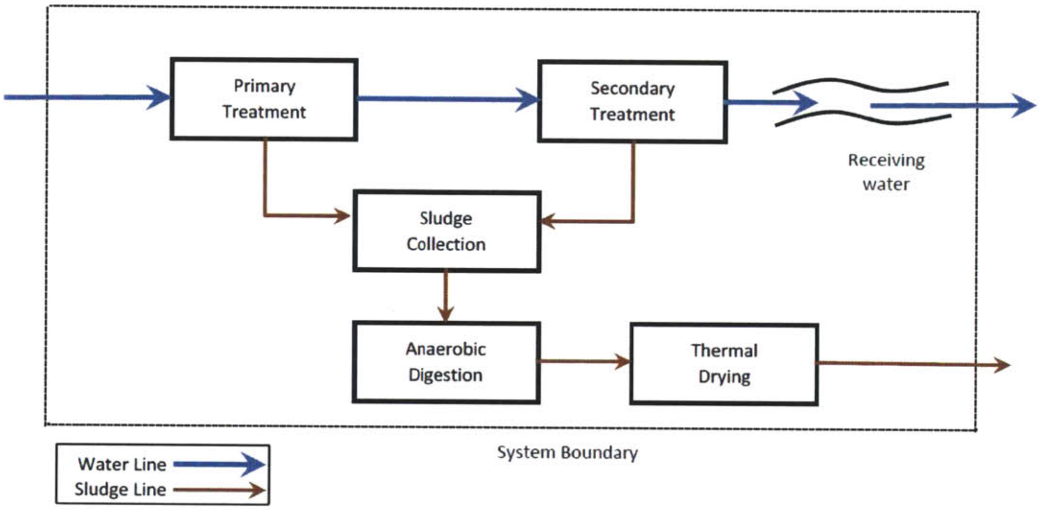


Figure 3.1 System Boundary of the La Gavia WWTP

3.3. GaBi 5 Software

The GaBi 5 is the most updated version of the GaBi software, developed by PE International. The GaBi 5 software system offers access to comprehensive and user-friendly functionality to analyze product life cycles or process technologies. The software is able to deal with life cycle assessment (LCA), product carbon footprints, life cycle costs and other social and environmental applications. The software also allows access to the GaBi database, which contains thousands of processes and hundreds of processes. (PE America, 2012)

Within the GaBi 5 software, the treatment plant can be viewed as a huge 'plan', which includes several processes. In addition, the inputs and outputs for each process are modeled as ‘flows’. Figure 3.2 is from GaBi 5. It shows the La Gavia WWTP model in the softwaare interface. Each rectanglar box represents a process. Besides the wastewater treatment processes mentioned above, there are the electricity generation process, sludge transportation and yhe effluent discharging process. In the figure, each arrow-head line represents a flow. The blue lines represent water line. The brown line represent the sludge line. And the grey lines stand for either electricity or disel.

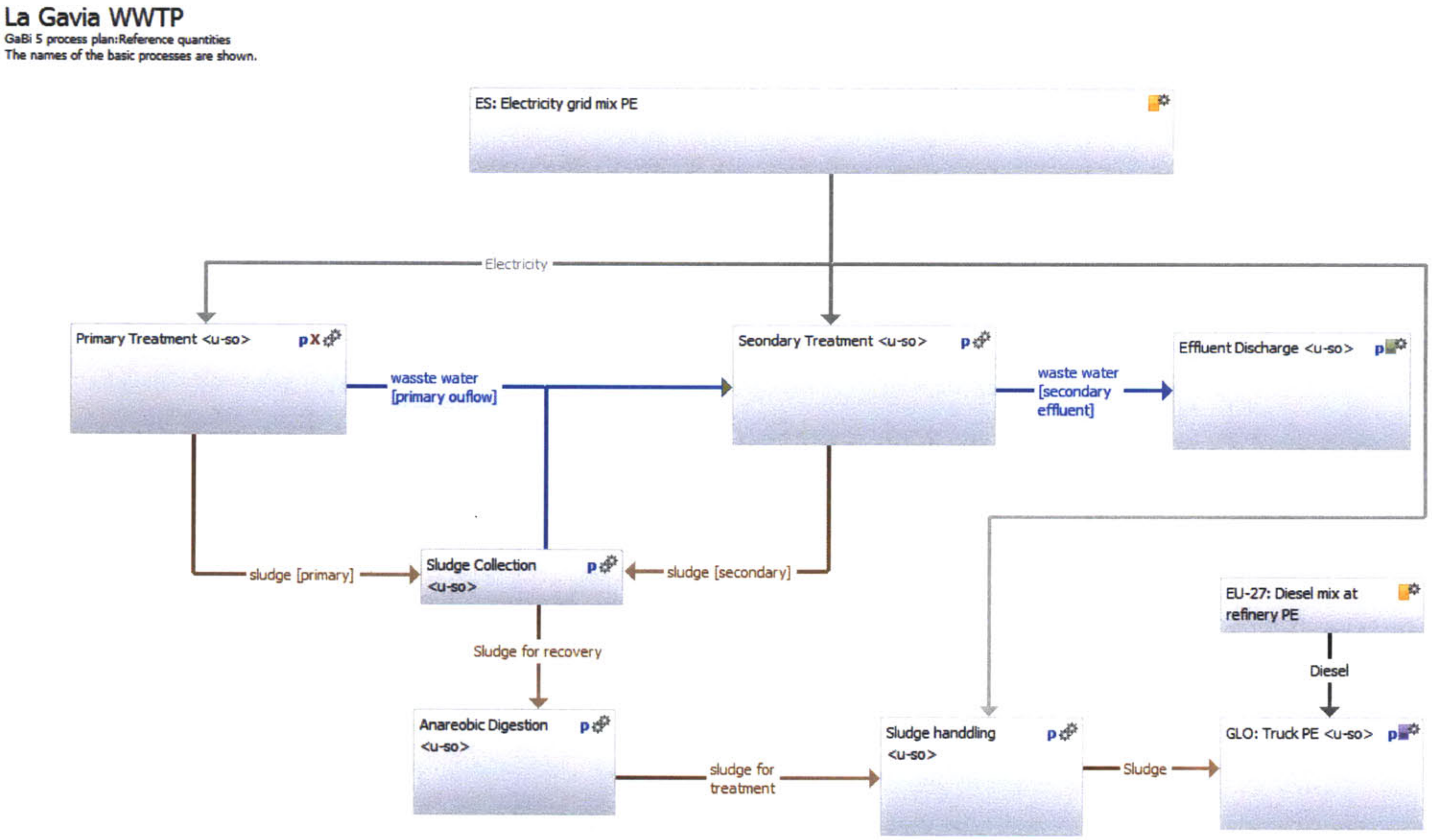


Figure 3.2 The La Gavia WWTP in GaBi 5

4. RESULTS

4.1. Life Cycle Inventory

The life cycle inventory analysis includes data collection, normalization, allocation and data evaluation. In this analysis, the normalization and allocation will be done by the GaBi 5 software.

4.1.1. Data Quality

With coordination from Cadagua S.A., the raw data are obtained from daily operation of the La Gavia WWTP in year 2011. The daily operational data are reported in the following categories: water flow, sludge, gas, energy, incidents and hours of operation. The detailed explanations for each category are shown Table 4.1 below:

Table 4.1 Reported Data Categories

Category	**Explanation**
Water Flow	Flow rate for each treatment process (primary, secondary, tertiary...) is recorded in volume (10^3 m^3)
Sludge	Sludge is reported in volume (m^3). It includes volumes for every sludge production and treatment process
Gas	Gas is generated from the anaerobic digestion process. It is used in boilers, cogenerators and torch. The amount of gas is reported for every source and sink. The reported unit is normal cubic meter (Nm^3)
Energy	Electricity consumptions for La Gavia come from two part, self-production and purchase. The reported unit is kWh.
Incidents	This category includes weather and operational incidents, such as rainfall and foaming
Hours of Operation	The WWTP operates continuously in a year. The hours of operation records operational hours of each engine (pump, boiler and etc.)

The raw data is further treated by taking a daily average. It represents the daily average quantity for treating 76040m^3/day (functional unit) of wastewater.

4.1.2. Mass Balance

In order to gain comprehensive understanding of the plant operational conditions, mass balances have been done on flow rate, total nitrogen and total phosphorus. The mass balance of carbon is not necessary and somehow complicated. Hence, the mass balance of carbon is not performed. In addition, the balance total energy consumptions has also been done in this section.

Flow rate

Figure 4.1 shows the overall mass balance of flow rate. For example, the primary treatment process receives 70640m^3/day of wastewater from the sewer system. After the treatment, 3200 m^3/day of sludge is generated, leaving 72840m^3/day of wastewater in the primary effluent.

These flow rates are the daily average for 2011. The original flow information is recorded on a daily basis (weekdays) from the end of December 2010 to the start of January of 2012. The arithmetic average is taken to offset seasonal variances. The numbers are all in m^3/day, except for the dried sludge, which is expressed as tonne/day.

Flow rate cannot be balanced perfectly, due to the discrepancies from measurements and other unknown sources and sinks (rainfall, leakage and overflow). However, the errors are less than two percent of total flow. In practice, the flow rates have been adjusted accordingly to ensure arithmetic consistency.

As discussed in Section 3.2.3., in La Gavia WWTP, tertiary treatment is a part of wastewater reuse. The flow rate for tertiary treatment (not shown in Figure 4.1) is about 0.5% of the total flow on average. Besides, the total environmental impacts from the tertiary treatment are reasonably small, due to the small amount of flow rate. Therefore, the impact assessment for tertiary treatment is excluded at this stage. Similar approximations have also been made on the bypassed flow.

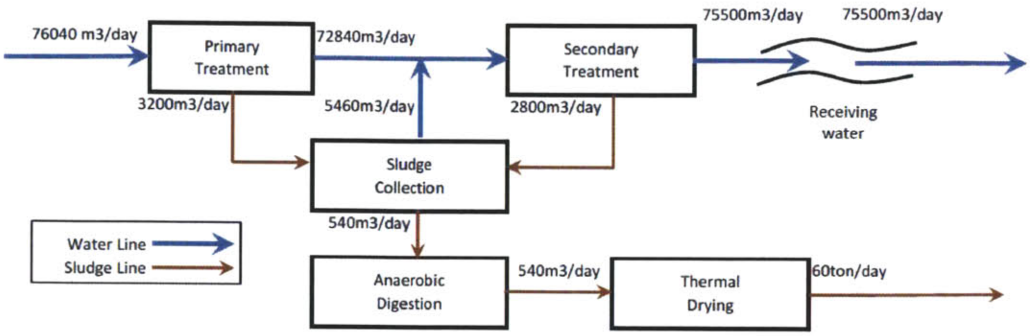


Figure 4.1 Mass Balance of Flow Rate

Nitrogen

Nitrogen is reported by the total nitrogen concentration and its relative content, namely, nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_4^+), and total Kjedahl nitrogen (TKN). Figure 4.2 shows the mass balance of total nitrogen. The unit is 'tonnes per day'. In general, total nitrogen can be calculated by the following formula:

Mass flow rate (mass/d) = Flow rate (volume/d) × Concentration (mass/volume)

For example, the total influent nitrogen, 4.72 ton/d, is the product of 76040 m^3/d and 62 mg/L.

The only exceptions are nitrous oxide (N_2O) and nitrogen gas (N_2). Since there is no direct way to calculate N_2O, the EPA formula (USEPA, 2011) is used:

$$\mathbf{N_2O = Population \times EF \times F_{IND\text{-}COM}}$$

where,

N_2O:	N_2O emissions from centralized wastewater treatment plants with nitrification /denitrification (g/year)
Population:	Population of the service area
EF:	Emission factor (7 g N_2O/person-year) – plant with intentional denitrification
$F_{IND\text{-}COM}$:	Factor for industrial and commercial co-discharged protein into the sewer system (1.25)

The total population in La Gavia service area is estimated as 950,000. Therefore, N_2O direct emission is roughly 0.022ton/d. We can also express N2O in total nitrogen (N-N_2O), which is 0.0126ton/day.

During secondary treatment, the nitrogen sources are from the primary effluent and the recycled sludge. The sinks, on the other hand, include secondary effluent, secondary sludge, nitrous oxide and the nitrogen gas (N_2). Nitrogen gas can be then calculated by mass balance.

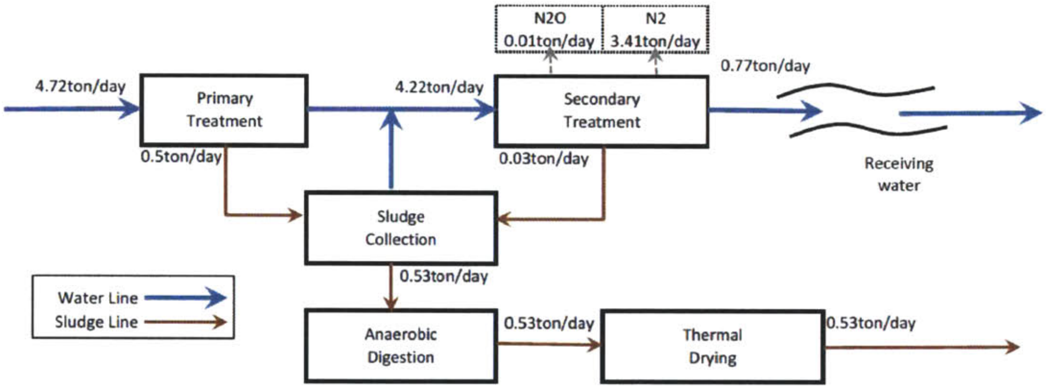


Figure 4.2 Mass Balance of Nitrogen

Phosphorus

Compared with nitrogen, phosphorus is easier and analyze. Figure 4.3 shows the mass balance of total phosphorus. Phosphorus is removed by the addition of ferric chloride ($FeCl_3$). The total phosphorus is reported by the amount of inorganic phosphorus (PO_4^-) and organic phosphorus.

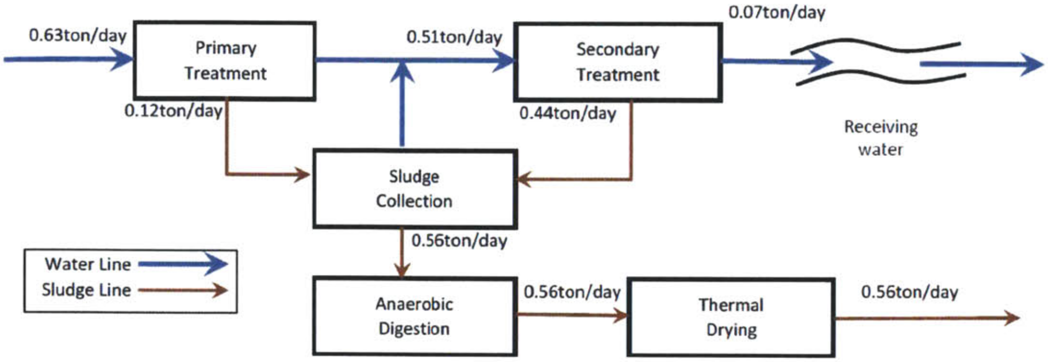


Figure 4.3 Mass Balance of Phosphorus

Energy

The total energy consumption is reported by the total amount of electricity purchased per year and the amount of electricity generated within the plant (through energy recovery from digester gas). However, to study the contribution of the energy consumption for each process, we can estimate the amount of electricity by the product of the machine size and the hours of operation. Table 4.2 is the summary for electricity. The first column shows the theoretical electricity consumption. These numbers represent the total electricity usage in plant operation, including primary treatment, secondary treatment, and sludge treatment.

In order to calculate how much electricity is purchased for each process. The conversion factor is defined. For example, the primary treatment process used 8719 kWh electricity in total, which is 25.9 % (8719/33650) of total electricity usage. Therefore, the purchased electricity for the primary treatment process is: 25040 kWh × 25.9% = 6488kWh.

In fact, besides the three items listed in Table 4.2, the La Gavia WWTP may also include other electricity consumption sources, such as electricity in office utilities. However, the electricity from office utilities is only a very part. Hence, in this analysis, this amount of electricity is not calculated separately, but incorporated into the total electricity purchased.

Table 4.2 Electricity Summary

	Theoretical electricity consumption (kWh)	Total Electricity purchased (kWh)	Conversion factor	Weighted electricity purchased (kWh)
Primary	8719	-	(8719/33650)* 25040	6488
Secondary	21099		(21099/33650)* 25040	15700
Sludge	3832		(3832/33650)* 25040	2852
Total	33650	25040	(33650/33650)* 25040	25040

Carbon

The direct emissions of carbon related gases, such as CO_2 and CH_4, have been included in the LCA model, using various approximations. Figure 4.4 shows the direct emissions of CO_2 and CH_4 from the La Gavia WWTP. It is not necessary to perform the mass balance of carbon. Besides, the mass balance of carbon also requires additional data, such as the chemical composition of wastewater in the Cadagua service area and the amount of direct CO_2 emission.

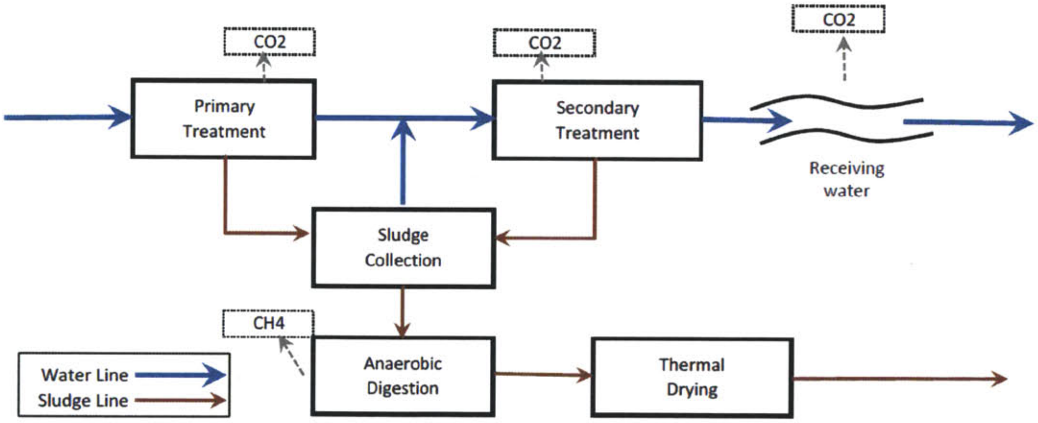


Figure 4.4 Direct Emissions of CO_2 and CH_4

The direct emission of CO_2 includes aerobic degradation from the primary and secondary treatment processes, as well as in the downstream receiving water. According to USEPA (2011), the biogenic CO_2 from waste management system would not affect the timing and location of the CO_2 emission, because these carbon sources would have been returned to the atmosphere as CO_2 due to natural decay. These direct emissions of CO_2 would not change carbon in the short carbon cycle, which is quite different from the CO_2 emission from fossil fuel combustion. Previous research (e.g. Tillman et.al, 1998) has also adopted this framework, so by convention biogenic CO2 emission is not considered.

Methane gas, generated in anaerobic digestion of sludge, is another carbon related direct emission, other than CO_2. Cadugua S.A. reports on the total amount of digester gas in Nm^3. La Gavia WWTP has good management of methane, which is used in cogeneration. However, there is still emission of CH_4 from incomplete combustion. USEPA (2011) has given recommendations on the quantification of the CH_4 direct emissions. The EPA formula is shown below:

$$\mathbf{CH_4 = methane\ production\ rate \times (1 - DE) \times density\ of\ methane}$$

where,

CH_4:	CH_4 emissions from anaerobic sludge treatment process (g/day)
Methane production rate:	Amount of methane produced in the anaerobic digestion process (Nm^3)
DE:	Methane destruction efficiency (0.99 for enclosed flares)
Density of methane:	662 g/m^3

The calculation is based on the total amount of methane production and the combustion destruction rate of 99%, recommended by EPA. From the formula, it is clear that CH_4 is based on (1 – DE), with DE = 0.99. Hence, the amount of CH_4 is quite sensitive the DE value. For example, if DE is changed from 99% to 98%, then (1 – DE) would change from 1% to 2%. Therefore, the amount of CH_4 would also double.

4.1.3. Life Cycle Inventory of the La Gavia WWTP

In order to conduct LCA using GaBi 5, it is necessary to analyze the inputs and outputs for each individual process. The inputs and outputs data are mainly based on the mass balance results and estimation using empirical formulas. The table below is the complete list of inputs and outputs for the La Gavia WWTP.

Table 4.3 List of Inputs and Outputs for the La Gavia WWTP

Primary Treatment		
Inputs		
Waste water [primary inflow]	76040	m3
Electricity [Electric power]	6511.7	kWh
Outputs		
sludge [primary] [Waste for recovery]	3200	m3
waste water [primary outflow]	72840	m3

Secondary Treatment		
Inputs		
waste water [primary outflow]	78300	m3
Electricity [Electric power]	15703	kWh
Outputs		
sludge [secondary] [Waste for recovery]	2800	m3
waste water [secondary effluent]	75500	m3
Nitrous oxide [Inorganic emissions to air]	22.8	kg

Effluent discharge		
Inputs		
waste water [secondary effluent]	75500	m3
Outputs		
waste water [Waste for disposal]	75500	m3

Sludge collection		
Inputs		
sludge [secondary]	2800	m3
sludge [primary]	3200	m3
Outputs		
Sludge for recovery	540	m3
waste water [primary outflow]	5460	m3

Anaerobic digestion		
Inputs		
Sludge for recovery	540	m3
Outputs		
Digested sludge	540	m3
Methane [Organic emissions to air]	37.1	kg

Sludge Handling		
Inputs		
sludge for treatment	540	m3
Electricity [Electric power]	2830	kWh
Outputs		
Sludge [Hazardous waste]	60000	kg

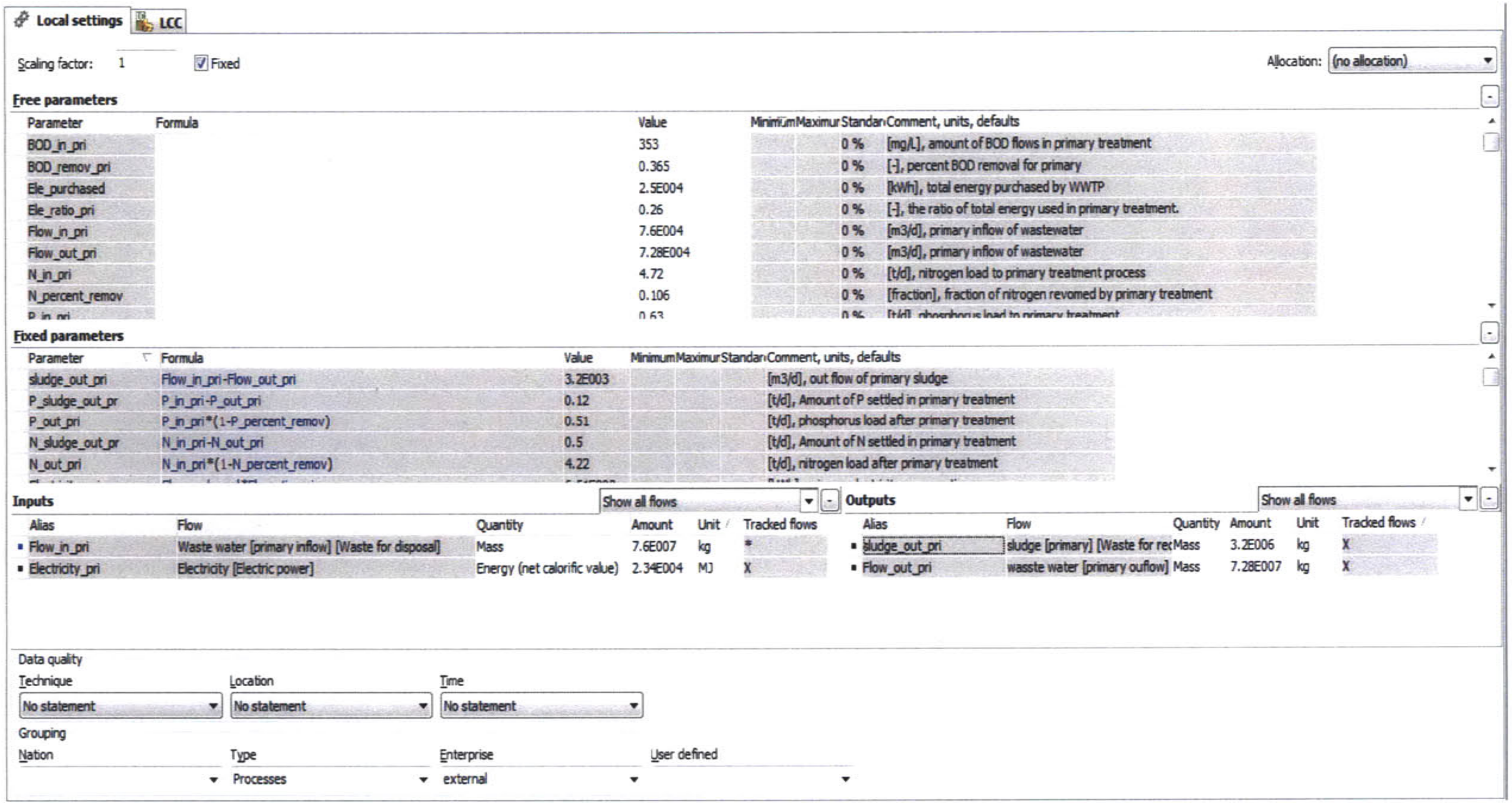
Transportation		
Inputs		
Diesel [Refinery products]	408.6	kg
Sludge [Hazardous waste]	60000	kg
Outputs		
Sludge [Hazardous waste]	60000	kg

4.1.4. Gabi 5 Modeling

As discussed in Section 3.3, the La Gavia WWTP has been modeled as a huge 'plan'. Similarly, each treatment process is modeled as a 'process' and inputs and outputs are treated as 'flows'. Figure 4.5 shows how primary treatment is modeled in GBi 5 interface.

The process interface is divided into four main sections: free parameters, fixed parameters, inputs and outputs. It is easy to translate inputs and output data from the LCI results from Section 4.1.2 to GaBi flows. For example, the inputs for primary treatment are raw wastewater and electricity, while the outputs are primary effluent and primary sludge. One column is named ‘tracked flow’. It is used to determine the fate of each flow. ‘X’ means the flow is tracked, which either comes from a previous process or goes to the next process. ‘*’ means the flow is a waste flow. And a space (‘ ‘) means an elementary flow, such as carbon dioxide, water, and etc.

The free parameters, which are allowed to change for each instance, are used to describe both the quality and quantity of flows. For example, wastewater could contain biochemical oxygen demand (BOD) and total nitrogen. The information is recorded in the parameters, which are carried along the whole plan. The fixed parameters are also used to describe flows, but they are not allowed to change for each instance.



Scaling factor: 1 ☑ Fixed

Allocation: (no allocation)

Free parameters

Parameter	Formula	Value	Minimum	Maximum	Standard	Comment, units, defaults
BOD_in_pri		353			0 %	[mg/L], amount of BOD flows in primary treatment
BOD_remov_pri		0.365			0 %	[-], percent BOD removal for primary
Ele_purchased		2.5E004			0 %	[kWh], total energy purchased by WWTP
Ele_ratio_pri		0.26			0 %	[-], the ratio of total energy used in primary treatment.
Flow_in_pri		7.6E004			0 %	[m3/d], primary inflow of wastewater
Flow_out_pri		7.28E004			0 %	[m3/d], primary inflow of wastewater
N_in_pri		4.72			0 %	[t/d], nitrogen load to primary treatment process
N_percent_remov		0.106			0 %	[fraction], fraction of nitrogen revomed by primary treatment
P_in_pri		0.63			0 %	[t/d], phosphorus load to primary treatment

Fixed parameters

Parameter	Formula	Value	Minimum	Maximum	Standard	Comment, units, defaults
sludge_out_pri	Flow_in_pri-Flow_out_pri	3.2E003				[m3/d], out flow of primary sludge
P_sludge_out_pr	P_in_pri-P_out_pri	0.12				[t/d], Amount of P settled in primary treatment
P_out_pri	P_in_pri*(1-P_percent_remov)	0.51				[t/d], phosphorus load after primary treatment
N_sludge_out_pr	N_in_pri-N_out_pri	0.5				[t/d], Amount of N settled in primary treatment
N_out_pri	N_in_pri*(1-N_percent_remov)	4.22				[t/d], nitrogen load after primary treatment

Inputs Show all flows

Alias	Flow	Quantity	Amount	Unit	Tracked flows
Flow_in_pri	Waste water [primary inflow] [Waste for disposal]	Mass	7.6E007	kg	*
Electricity_pri	Electricity [Electric power]	Energy (net calorific value)	2.34E004	MJ	X

Outputs Show all flows

Alias	Flow	Quantity	Amount	Unit	Tracked flows
sludge_out_pri	sludge [primary] [Waste for rec	Mass	3.2E006	kg	X
Flow_out_pri	wasste water [primary ouflow]	Mass	7.28E007	kg	X

Data quality

Technique	Location	Time
No statement	No statement	No statement

Grouping

Nation	Type	Enterprise	User defined
	Processes	external	

Figure 4.5 Primary Treatment Process in GaBi 5

4.2. Impact Assessment

4.2.1. Selected Impact Categories

Within the scope of this LCA, global warming potential (GWP) and eutrophication potential (EP) are the two impact categories of interest. It is general practice to include these two categories in WWTPs. This is because GWP provides the information for total carbon footprints, while EP is a good indicator for the performance of WWTPs. Although the GaBi 5 also provides the database for other impact categories, such as ozone depletion and natural source depletion, they are available only for certain processes and of less concern. Hence, these impact categories are not included in the final discussions.

As defined in Section 2.1.2, the standardized unit for global warming potential is kg CO_2-Eq. Similarly, the unit adopted for eutrophication potential kg phosphate-Eq.

4.2.2. Results from GaBi 5

Table 4.4 shows the results from GaBi 5. The impact categories are global warming potential and eutrophication potential. Each environmental impact is reported by the impact of each process and the total impact. The results are based on the functional unit of 76040m^3/day of wastewater treated. Hence, another way to interpret these numbers is to treat them as the daily impact from the La Gavia WWTP.

Table 4.4 LCIA Results from GaBi 5

	CML2001 - Nov. 2010 Global Warming Potential (GWP 100 years) kg CO_2 - Eq	CML2001 - Nov. 2010 Eutrophication Potential (EP) kg phosphate-Eq
Total	20316.82	225.65
Anaerobic Digestion	927.56	0.00
Effluent Discharge	0.00	214.40
Electricity	11169.20	2.88
Transportation	1433.41	2.22
Primary Treatment	0.00	0.00
Secondary Treatment	6786.64	6.15
Sludge Collection	0.00	0.00
Sludge handling	0.00	0.00

Figure 4.6 and Figure 4.7 show the degree to which each process contributes to global warming.

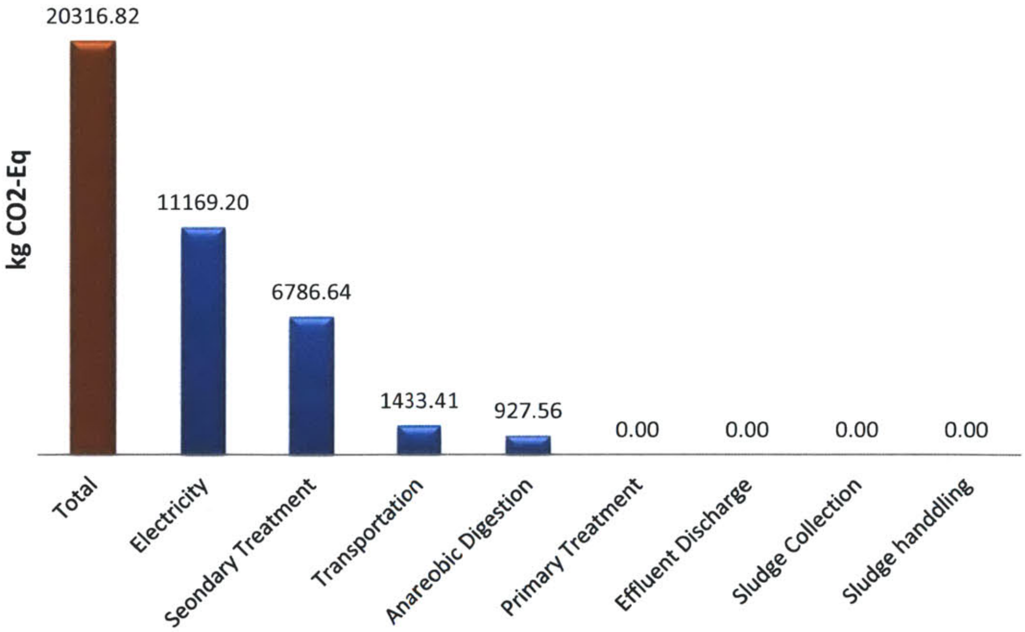


Figure 4.6 Global Warming Potential of the La Gavia WWTP

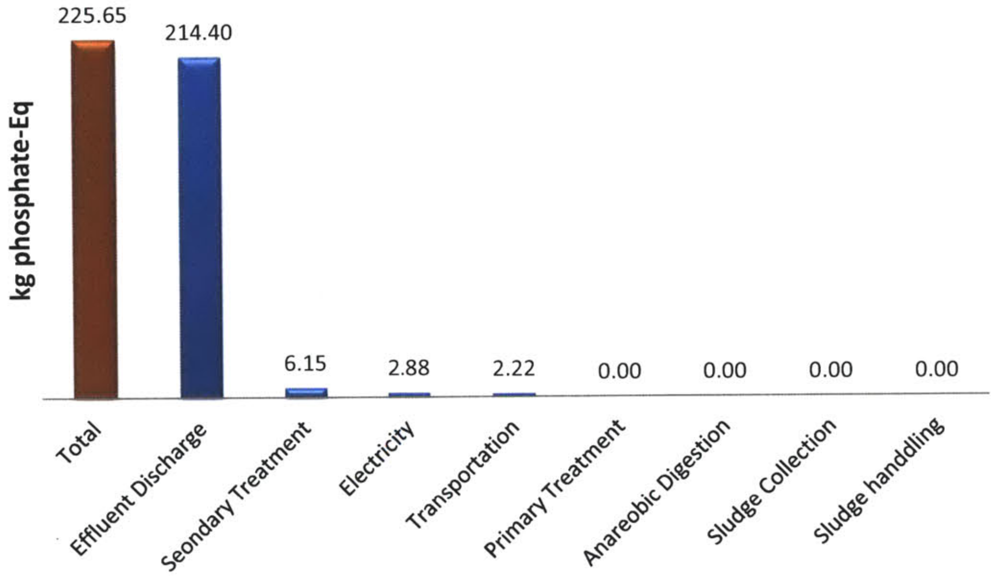


Figure 4.7 Eutrophication Potential of the La Gavia WWTP

In Figure 4.6, it is clear that more than 50% of the total greenhouse gas is from electricity consumption. This emission is caused by the indirect emissions of CO_2 from the fossil fuel combustion in power plants. Following electricity, secondary treatment is the second largest source, which contributes about 33% of the total emission. In this LCA, this emission comes from mainly the direct emission of N_2O from the secondary treatment process (nutrient removal).

The emissions from transportation consist of two parts: the CO_2 emission from the truck and other emissions from oil refinery. Finally, the emission from the anaerobic digestion is caused by the incomplete combustion of CH_4.

From Figure 4.7, it is clear that the eutrophication is mainly caused by the effluent discharge, which contains the total nitrogen and the total phosphorus residuals from the secondary effluent. The total eutrophication could be more significant for treatment plants without nutrient removal processes.

In addition to effluent discharge, about three percent of the eutrophication potential is contributed by the secondary treatment process, which emits nitrous oxide to the atmosphere. A certain amount of the nitrous oxide in the atmosphere is finally returned to surface water through precipitation. This part of nitrous oxide is counted in the eutrophication potential.

5. DISCUSSIONS

5.1. Sensitivity Analysis

As shown in the results section, the data sources vary by the type of gas. For example, the indirect emission of CO_2 is based on electricity consumptions, while the direct emissions of N_2O and CH_4 are from empirical formulas. The following paragraphs summarize conclusions and gives recommendation for each greenhouse gas.

The results for indirect CO_2 emission are from the electricity. In this LCA study, CML (Institute of Environmental Sciences) methodology is used for standardization, while other protocols are also available for different places of interest. The final results could change if different standards are adopted. However, in general, the final results should be very similar.

The emission of N_2O has huge variations and it is plant specific. International Panel on Climate Change (IPCC) and other researchers (Kampschreur et. al, 2009) have proposed different ranges on N_2O emission based on total nitrogen loading. The nitrous oxide emission for this LCA used the EPA formula, which is based on population. The real value could vary on an order of ten percent. Hence, for a more precise analysis, further studies on N_2O and direct measurements are needed. More discussions on the N_2O direct emissions from the secondary treatment process can be found in Xin Xu's report

Similar to the quantification of N_2O, CH_4 emission from the anaerobic digestion is also based on an empirical formula, which is derived from methane destruction rate. The results have shown that this amount of methane counted for five percent of total greenhouse gas emissions. The results could be improved if the daily analysis of gas from the cogenerator is available.

5.2. La Gavia WWTP vs. No WWTP

One of the goals for this LCA is to analyze the impact of the La Gavia WWTP. Therefore, it is necessary to compare the La Gavia WWTP with the case of no WWTP at all.

Figure 5.1 shows the different boundaries of the two scenarios. The above scenario is the case of the La Gavia WWTP, which is the same as previous analyses. The box below shows the case without any treatment. Wastewater from the sewage collection system is directly discharged into the receiving water (Manzanares River), without any treatment.

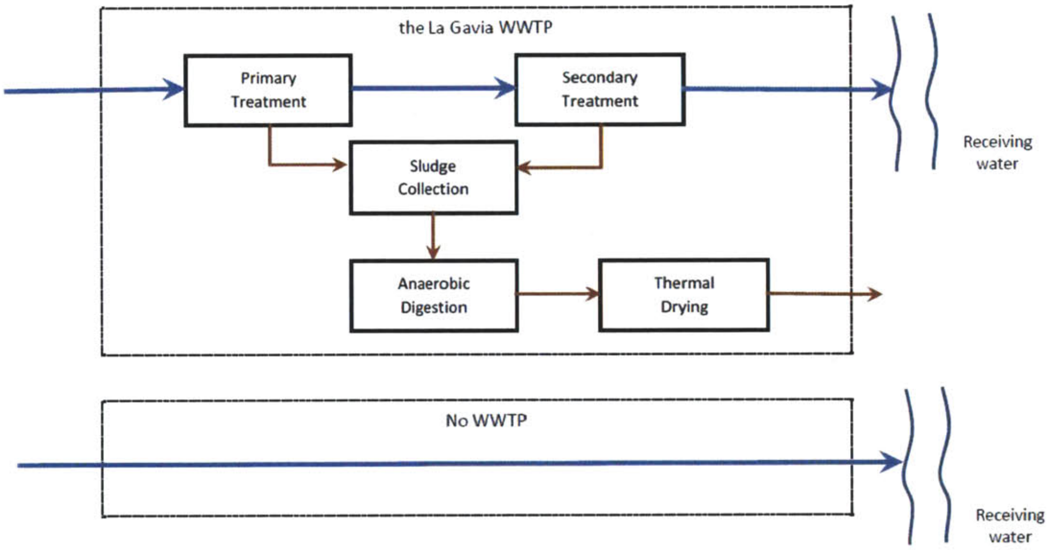


Figure 5.1 Comparisons between the La Gavia WWTP and No WWTP

Several assumptions have been for the case of without any treatment:

- No indirect GHG emission for the case without any treatment, because no electricity consumptions or transportation required;
- No direct emission is included for the case without any treatment, because it is assumed that aerobic condition will always hold in Manzanares River. The La Gavia WWTP has flow rate of 76040m^3/day, while Manzanares River has flow rate of 1036800 m^3/day. Therefore, if wastewater, with BOD concentration of 353 mg/L, is discharged into Manzanares River with zero upstream BOD, the mixed

BOD concentration would be 24.1 mg/L. This assumption might be reasonable with a very high reaeration rate;

- The nutrients in the untreated wastewater are discharged into Manzanares River. They are counted toward eutrophication potential.

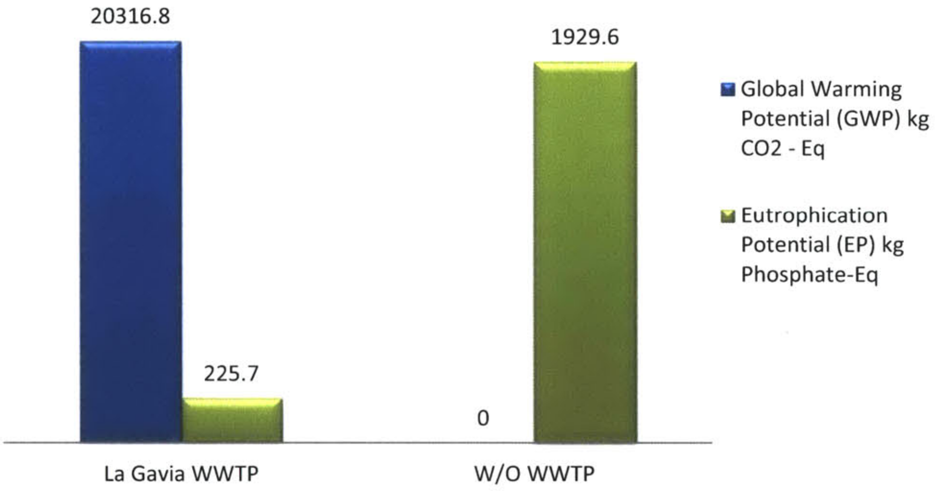


Figure 5.2 Comparison between GWP and EP

The final results of GWP and EP for both scenarios are shown in Figure 5.2. For GWP, the La Gavia WWTP emitted 20000 kg CO_2-Eq of GHG, while zero emission for the case without any treatment. However, for eutrophication, the La Gavia WWTP has better performance. It has the EP of 226 kg phosphate-Eq, compared with the EP of 2000 kg phosphate-Eq for the case without any treatment.

The model for the case of no WWTP is made with the assumptions that aerobic conditions would hold along the stream. However, as suggested above, it may not accurate in the real world. The following discussions show the drawbacks of the previous model:

- For the case of no WWTP, the model assumes instantaneous mixing once wastewater is discharged into Manzanares River. The BOD concentration could be higher than 24 mg/L if incomplete mixing occurs.
- The average concentration of 24 mg/L is calculated by mass balance, with zero BOD from upstream. However, there are several WWTPs located in the upstream of Manzanares River. Thus the real average BOD concentration after mixing could be higher than 24 mg/L

The rise in BOD would likely lead the stream to an anaerobic condition, which further causes anaerobic methane production. This amount of methane should be added to the global warming potential for the case of no WWTP. However, the exact amount of GWP is determined by many factors, such as BOD reduction rate and reaeration rate.

Another issue for interpreting the final results is how to normalize two different environmental impact categories. The GWP is more on a global scale, while EP is localized within the stream. On the one hand GWP would raise the issue of global warming, sea level rise and climate change. These effects would affect the living environment of Madrid area slowly and indirectly. On the other hand, EP would have rapid and direct effects on local environment, such as eutrophication, water quality, odor and aesthetics.

The results shown above have provided analyses of GWP and EP of WWTPs. It has also built the foundations for further research, such as whether a higher level of wastewater treatment (i.e., biological nutrient removal) is necessary for the sake of total environmental impact, i.e. should eutrophication potential be sacrificed for the total carbon footprints, or vice versa.

REFERENCES

- Cadagua S.A. (2011) company profile http://www.ferrovial.com/en/Business-Lines/Activities-Construction-Cadagua
- Climate Change 2007: Synthesis Report, IPCC 2007 http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm
- Crawford, G. H. (2011) *Life Cycle Assessment in the built environment* Spon Press. p38-70
- Emmerson, R.H.C., Morse G.K., Lester, J.N. (1995) ''The Life-Cycle Analysis of Small Scale Sewage-Treatment Processes'' *Int. J. CIWEM* 1995, 9, June
- Graedel, T.E. (1998) *Streamline Life-Cycle Assessment* Prentice Hall, Upper Sddle River, New Jersey 1998 p18-67.
- Halleux, H., Lassaux, S., Germain, A. (2006) Comparison of life cycle assessment methods, application to wastewater treatment plants. Conference proceedings
- Hernanz, S. (2007). Tertiary Treatment at the La Gavia Wastewater Treatment Plant, Madrid (Plant Report) http://wtert.de/default.asp?Menue=1&ArtikelPPV=9749
- Hospido A., Moreira, M.T., Couto, M.F., Feijoo,G. (2004) ''Environmental Performance of a Municipal Wastewater Treatment Plant'' Int. J. LCA 9(4) 261-271.
- Hospido, A., Moreira, M.T., Feijoo, G. (2008) ''A comparison of Municipal Wastewater Treatment Plants for Big Centers of Population in Galicia (Spain),'' *Int. J. LCA* 13(1) 57-64.
- International Standard 14040 (2006) Environmental Management – Life cycle assessment – Principles and framework
- Knosby, M., Mosteller, K., McClelland, J., Jarrell, J. Integrating Carbon Footprint Analysis into the Sugar Creek WWTP Expansion Project http://www.ncsafewater.org/Pics/Training/AnnualConference/AC09TechnicalPapers/AC09_SpecialTopics/ST_M.PM.2.45_Knosby.pdf
- Lassax S., Renzoni, R., Germain, A. (2007) ''Life Cycle Assessment of Water from the Pumping Station to the Watewater Treatment Plant'' *Int. J. LCA* 12(2) 118-126

- Lundie, S., Peters, G.M., Beavis, P.C. (2004) ''Life Cycle Assessment for Sustainable Metropolitan Water Systems Planning,'' *Environ. Sci. and Technol.*, vol 38, 3465-3473
- PE America, (2011) basic training brochure
- Richard, I. S., (1991) Phosphorus and Nitrogen Removal From Municipal Wastewater: Principles and Practice, CRC Press
- Sedlak,R. (1991). *Phosphorus and nitrogen removal from municipal wastewater: principles and practice* 2nd ed. Chelsea, Mich.: Lewis Publishers
- Sonnemann, G., Castells, F., Schuhmacher, M. (2004) *Integrated Life-Cycle and Risk Assessment for industrial processes* Lewis Pubilishers 2004 p37-54
- Suh Y.J., Rousseaux P. 2001 Condieration in Life Cycle Inventory Analysis of Municipal Wastewater Systems. Oral presentation at COST 624 WG meeting, Bologna, Italy http://www.ensic.u-nancy.fr/COSTWWTP/Work_Group/Wg3/Bologna/Suh_pres.pdf
- Şusana, H., (2007) Tertiary Treatment at the La Gavia Wastewater Treatment Plant, Madrid (Plant Report)
- Tillman, A.M., Svingby, M., Lundstrom, H. (1998) ''Life Cycle Assessment of Municipal Waste Water Systems'' *Int. J. LCA* 3(3) 145-157
- USEPA (2011) Inventory of U.S Greenhouse Gas Emissions and Sinks: 1990 – 2010 http://epa.gov/climatechange/emissions/downloads12/US-GHG-Inventory-2012-Main-Text.pdf
- USEPA (2006) *Life cycle assessment: principles and practices.* http://www.epa.gov/nrmrl/std/lca/pdfs/600r06060.pdf
- USEPA (2011) *Accounting Frame Work for Biogenic CO_2 Emissions from Stationary Sources* p40 http://www.epa.gov/climatechange/emissions/downloads/Biogenic_CO2_Accounting_Framework_Report_Sept_2011.pdf

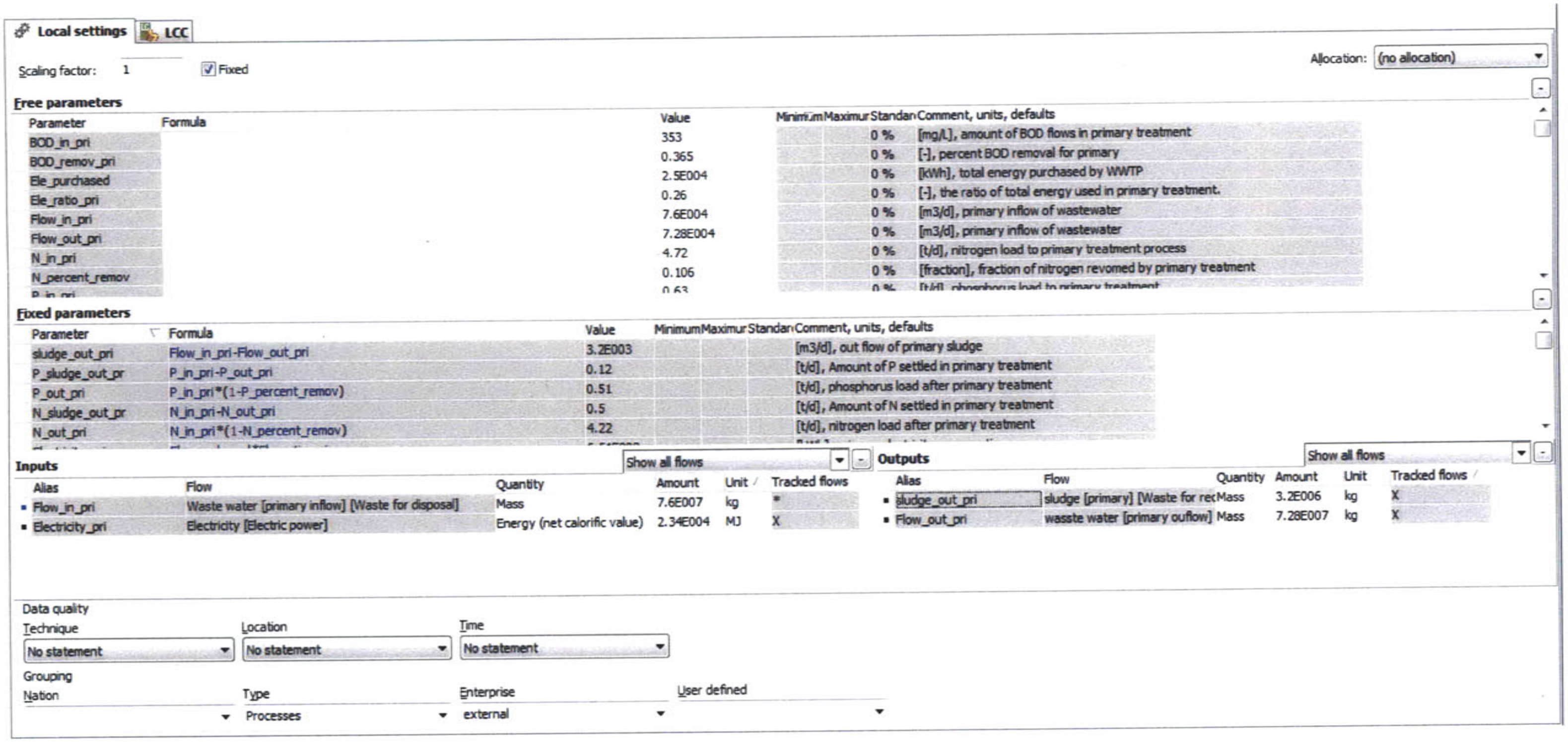
APPENDIX A

Summary of Electricity Usage

Primary					Secondary					Sludge treatment				
Pump Name	Size (kW)	NO. of pumps	Hours (hr/d)	Electricity Consumption (Kwh/d)	Pump Name	Size (kW)	NO. of pumps	Hours (hr/d)	Electricity Consumption (Kwh/d)	Pump Name	Size (kW)	NO. of pumps	Hours (hr/d)	Electricity Consumption (Kwh)
Pump 1 (collector sur)	85	2+1	18	4590	Turbo compressor 1	560	3+1	8.4	18816	Multi-stage Compppressor	50	2+1	7.8	1170
	80	6+1	4.9	2744	pump 2 (phosphorus removal)	0.81	6+1	5	28.35	dewatering	55	4	12.1	2662
Pump3 (Desarenado desengrado)	20	4+1	10	1000	pump 3 (recirculacion fangos)	30	6+1	10	2100					
Pump 4 (Purga de primarios)	5.5	6+1	10	385	pump 4 (wasted sludge)	3.1	4+1	10	155					
				8719					21099.35					3832

APPENDIX B

Primary Treatment Process



Scaling factor: 1 ☑ Fixed

Allocation: (no allocation)

Free parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Comment, units, defaults
BOD_in_pri		353			0 %	[mg/L], amount of BOD flows in primary treatment
BOD_remov_pri		0.365			0 %	[-], percent BOD removal for primary
Ele_purchased		2.5E004			0 %	[kWh], total energy purchased by WWTP
Ele_ratio_pri		0.26			0 %	[-], the ratio of total energy used in primary treatment.
Flow_in_pri		7.6E004			0 %	[m3/d], primary inflow of wastewater
Flow_out_pri		7.28E004			0 %	[m3/d], primary inflow of wastewater
N_in_pri		4.72			0 %	[t/d], nitrogen load to primary treatment process
N_percent_remov		0.106			0 %	[fraction], fraction of nitrogen revomed by primary treatment
P_in_pri		0.63			0 %	[t/d], phosphorus load to primary treatment

Fixed parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Comment, units, defaults
sludge_out_pri	Flow_in_pri-Flow_out_pri	3.2E003				[m3/d], out flow of primary sludge
P_sludge_out_pr	P_in_pri-P_out_pri	0.12				[t/d], Amount of P settled in primary treatment
P_out_pri	P_in_pri*(1-P_percent_remov)	0.51				[t/d], phosphorus load after primary treatment
N_sludge_out_pr	N_in_pri-N_out_pri	0.5				[t/d], Amount of N settled in primary treatment
N_out_pri	N_in_pri*(1-N_percent_remov)	4.22				[t/d], nitrogen load after primary treatment

Inputs

Show all flows

Alias	Flow	Quantity	Amount	Unit	Tracked flows
Flow_in_pri	Waste water [primary inflow] [Waste for disposal]	Mass	7.6E007	kg	*
Electricity_pri	Electricity [Electric power]	Energy (net calorific value)	2.34E004	MJ	X

Outputs

Show all flows

Alias	Flow	Quantity	Amount	Unit	Tracked flows
sludge_out_pri	sludge [primary] [Waste for rec	Mass	3.2E006	kg	X
Flow_out_pri	wasste water [primary ouflow]	Mass	7.28E007	kg	X

Data quality

Technique: No statement

Location: No statement

Time: No statement

Grouping

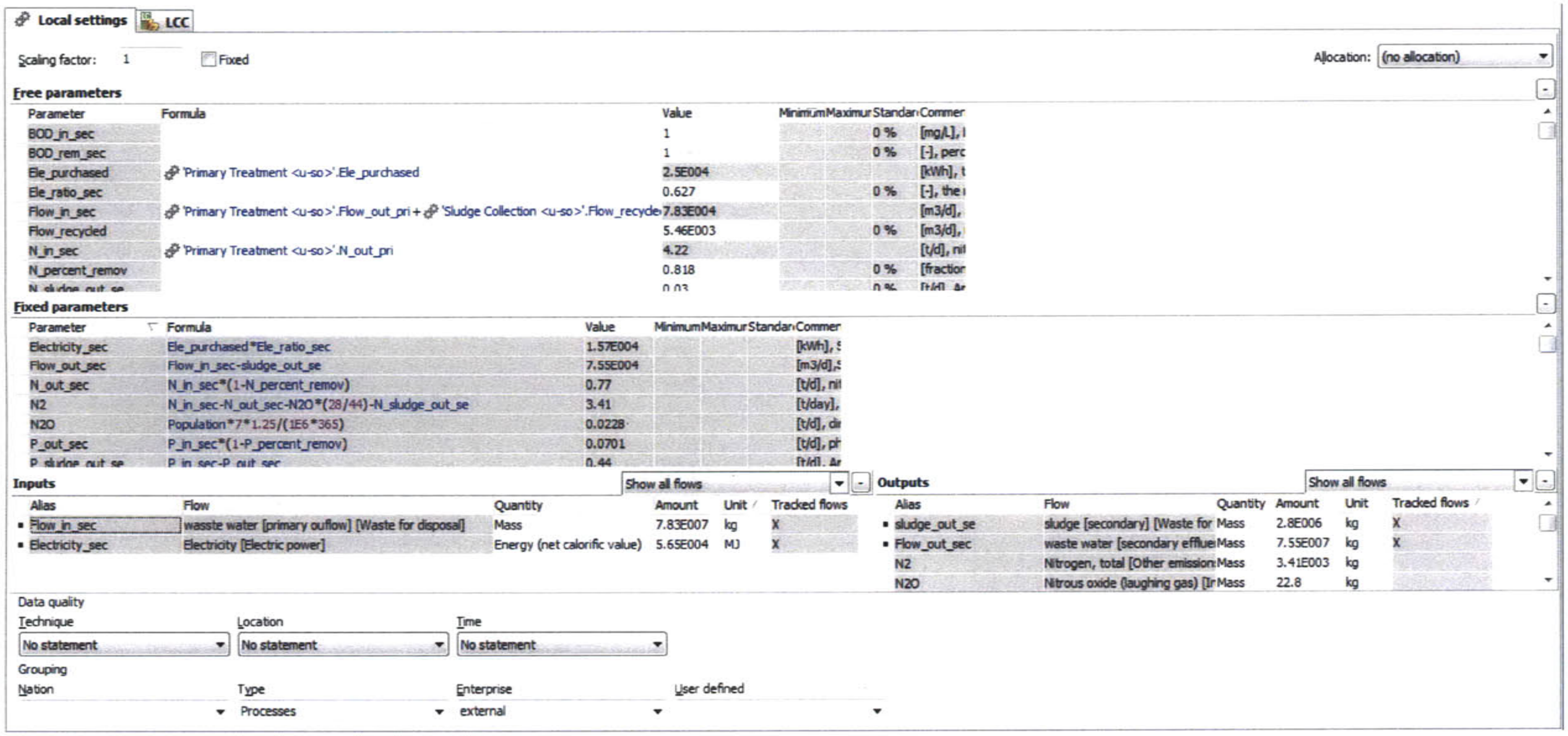
Nation:

Type: Processes

Enterprise: external

User defined:

Secondary Treatment Process



Scaling factor: 1 ☐ Fixed

Allocation: (no allocation)

Free parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
BOD_in_sec		1			0 %	[mg/L], I
BOD_rem_sec		1			0 %	[-], perc
Ele_purchased	'Primary Treatment <u-so>'.Ele_purchased	2.5E004				[kWh], t
Ele_ratio_sec		0.627			0 %	[-], the
Flow_in_sec	'Primary Treatment <u-so>'.Flow_out_pri + 'Sludge Collection <u-so>'.Flow_recycle	7.83E004				[m3/d],
Flow_recycled		5.46E003			0 %	[m3/d],
N_in_sec	'Primary Treatment <u-so>'.N_out_pri	4.22				[t/d], nit
N_percent_remov		0.818			0 %	[fraction
N_sludge_out_se		0.03			0 %	[t/d], Ar

Fixed parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Electricity_sec	Ele_purchased*Ele_ratio_sec	1.57E004				[kWh], S
Flow_out_sec	Flow_in_sec-sludge_out_se	7.55E004				[m3/d],S
N_out_sec	N_in_sec*(1-N_percent_remov)	0.77				[t/d], nit
N2	N_in_sec-N_out_sec-N2O*(28/44)-N_sludge_out_se	3.41				[t/day],
N2O	Population*7*1.25/(1E6*365)	0.0228				[t/d], di
P_out_sec	P_in_sec*(1-P_percent_remov)	0.0701				[t/d], ph
P_sludge_out_se	P_in_sec-P_out_sec	0.44				[t/d], Ar

Inputs Show all flows

Alias	Flow	Quantity	Amount	Unit	Tracked flows
Flow_in_sec	wasste water [primary ouflow] [Waste for disposal]	Mass	7.83E007	kg	X
Electricity_sec	Electricity [Electric power]	Energy (net calorific value)	5.65E004	MJ	X

Outputs Show all flows

Alias	Flow	Quantity	Amount	Unit	Tracked flows
sludge_out_se	sludge [secondary] [Waste for	Mass	2.8E006	kg	X
Flow_out_sec	waste water [secondary efflue	Mass	7.55E007	kg	X
N2	Nitrogen, total [Other emission	Mass	3.41E003	kg	
N2O	Nitrous oxide (laughing gas) [In	Mass	22.8	kg	

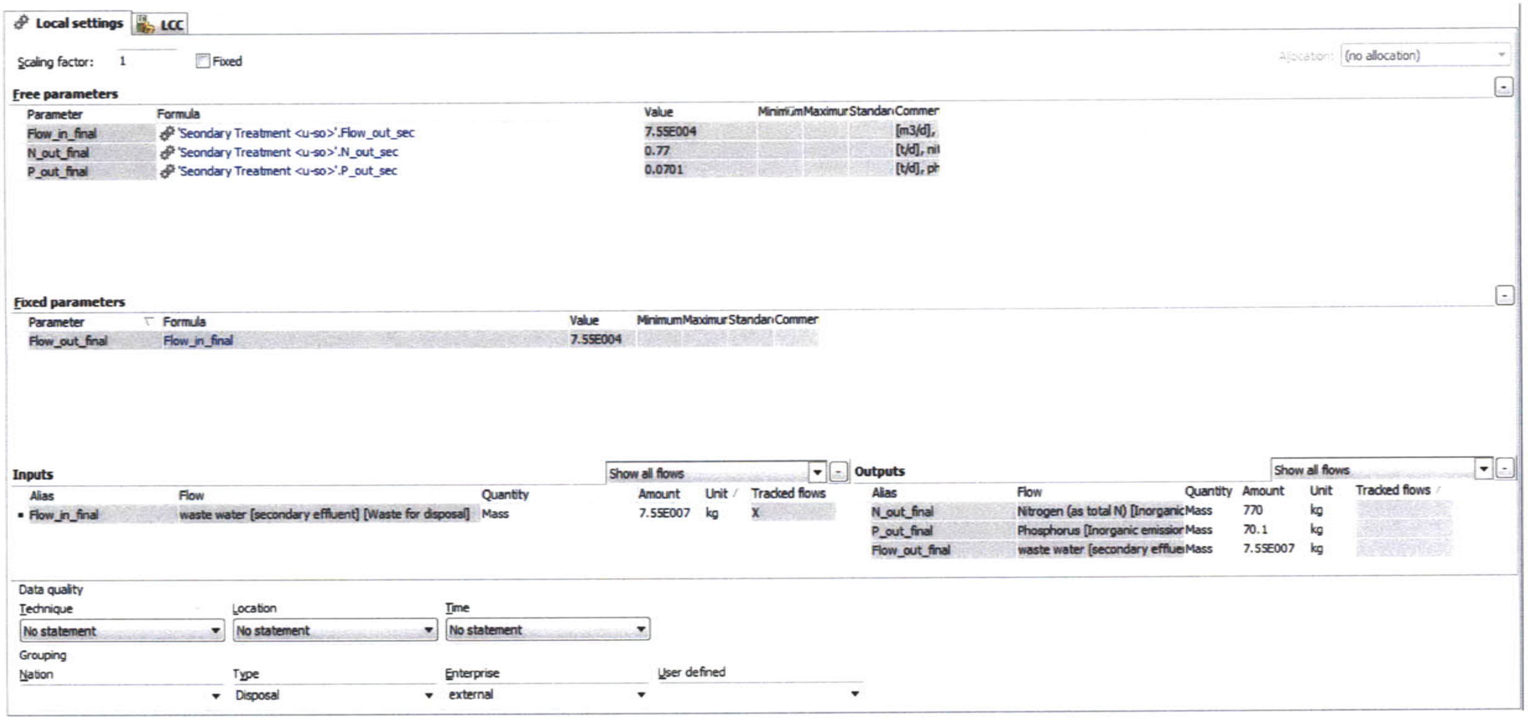
Data quality

Technique: No statement
Location: No statement
Time: No statement

Grouping

Nation:
Type: Processes
Enterprise: external
User defined:

Effluent Discharge



Scaling factor: 1 ☐ Fixed

Allocation: (no allocation)

Free parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Flow_in_final	'Seondary Treatment <u-so>'.Flow_out_sec	7.55E004				[m3/d],
N_out_final	'Seondary Treatment <u-so>'.N_out_sec	0.77				[t/d], ni
P_out_final	'Seondary Treatment <u-so>'.P_out_sec	0.0701				[t/d], ph

Fixed parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Flow_out_final	Flow_in_final	7.55E004				

Inputs

Show all flows

Alias	Flow	Quantity	Amount	Unit	Tracked flows
Flow_in_final	waste water [secondary effluent] [Waste for disposal]	Mass	7.55E007	kg	X

Outputs

Show all flows

Alias	Flow	Quantity	Amount	Unit	Tracked flows
N_out_final	Nitrogen (as total N) [Inorganic	Mass	770	kg	
P_out_final	Phosphorus [Inorganic emission	Mass	70.1	kg	
Flow_out_final	waste water [secondary efflue	Mass	7.55E007	kg	

Data quality

Technique: No statement

Location: No statement

Time: No statement

Grouping

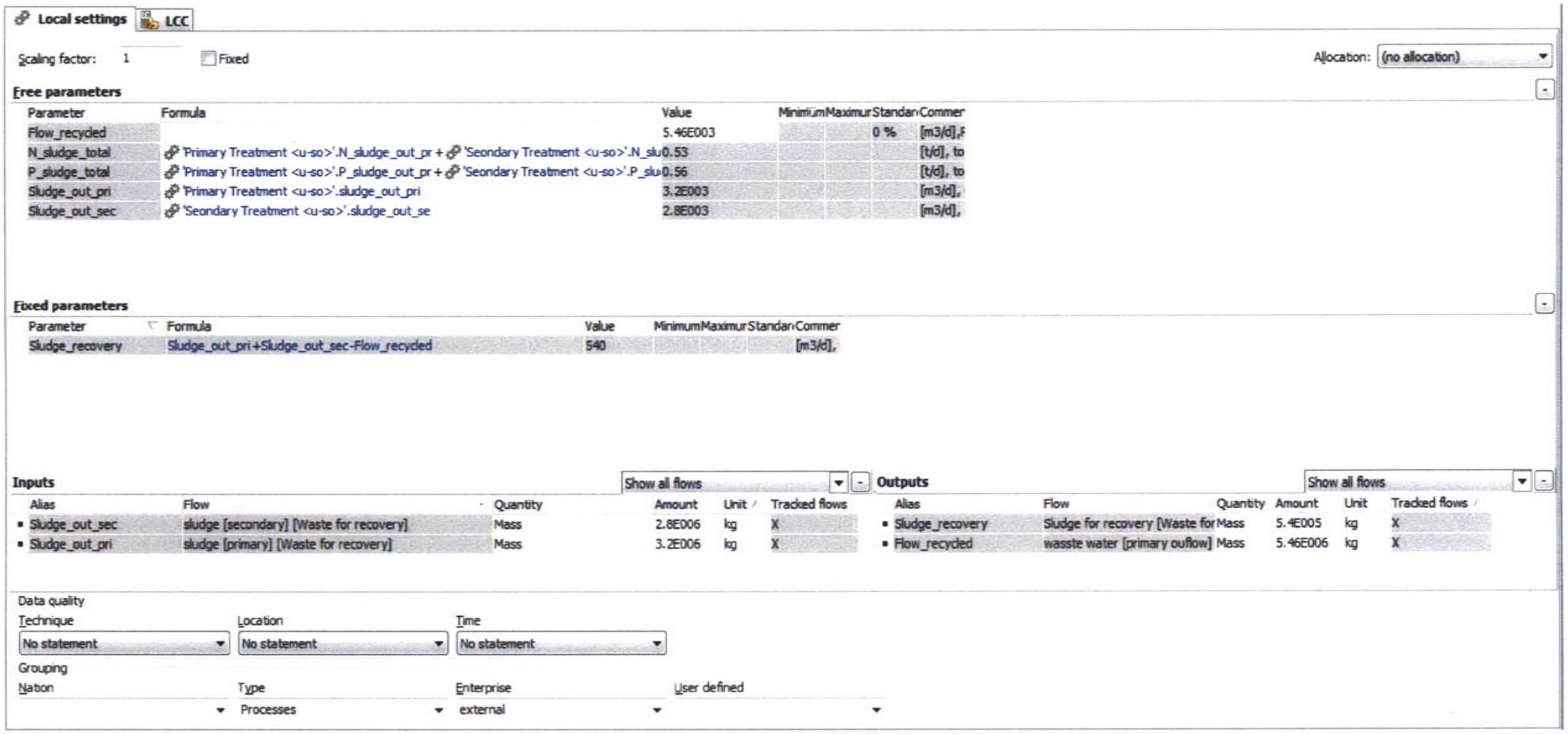
Nation:

Type: Disposal

Enterprise: external

User defined:

Sludge Collection



Scaling factor: 1 ☐ Fixed

Allocation: (no allocation)

Free parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Flow_recycled		5.46E003			0 %	[m3/d],F
N_sludge_total	'Primary Treatment <u-so>'.N_sludge_out_pr + 'Seondary Treatment <u-so>'.N_slu	0.53				[t/d], to
P_sludge_total	'Primary Treatment <u-so>'.P_sludge_out_pr + 'Seondary Treatment <u-so>'.P_slu	0.56				[t/d], to
Sludge_out_pri	'Primary Treatment <u-so>'.sludge_out_pri	3.2E003				[m3/d],
Sludge_out_sec	'Seondary Treatment <u-so>'.sludge_out_se	2.8E003				[m3/d],

Fixed parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Sludge_recovery	Sludge_out_pri+Sludge_out_sec-Flow_recycled	540				[m3/d],

Inputs Show all flows

Alias	Flow	Quantity	Amount	Unit	Tracked flows
Sludge_out_sec	sludge [secondary] [Waste for recovery]	Mass	2.8E006	kg	X
Sludge_out_pri	sludge [primary] [Waste for recovery]	Mass	3.2E006	kg	X

Outputs Show all flows

Alias	Flow	Quantity	Amount	Unit	Tracked flows
Sludge_recovery	Sludge for recovery [Waste for	Mass	5.4E005	kg	X
Flow_recycled	wasste water [primary ouflow]	Mass	5.46E006	kg	X

Data quality

Technique: No statement

Location: No statement

Time: No statement

Grouping

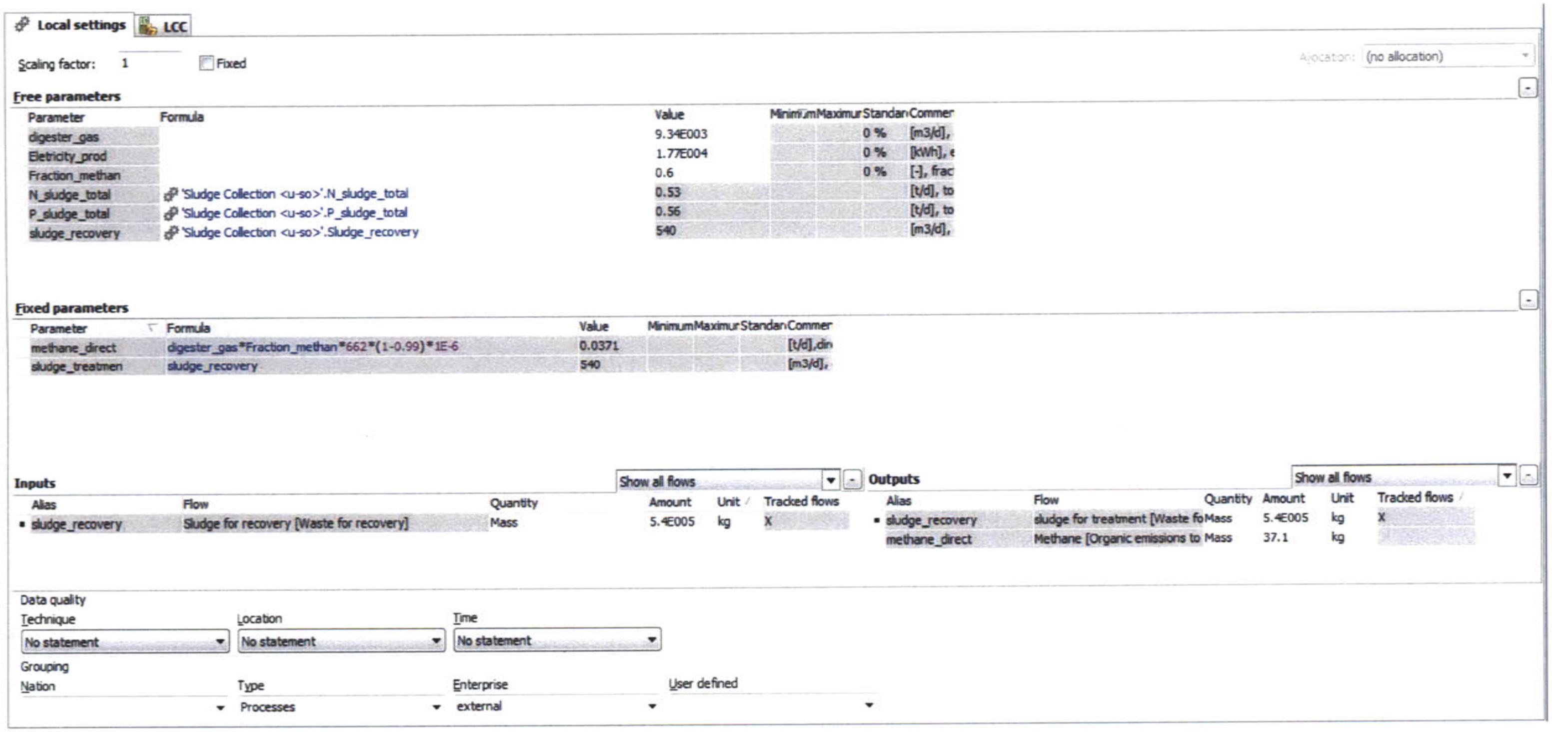
Nation:

Type: Processes

Enterprise: external

User defined:

Anaerobic Digestion



Scaling factor: 1 ☐ Fixed

Free parameters

Parameter	Formula	Value	Minimum	Maximum	Standard	Comment
digester_gas		9.34E003			0 %	[m3/d],
Eletricity_prod		1.77E004			0 %	[kWh], e
Fraction_methan		0.6			0 %	[-], frac
N_sludge_total	'Sludge Collection <u-so>'.N_sludge_total	0.53				[t/d], to
P_sludge_total	'Sludge Collection <u-so>'.P_sludge_total	0.56				[t/d], to
sludge_recovery	'Sludge Collection <u-so>'.Sludge_recovery	540				[m3/d],

Fixed parameters

Parameter	Formula	Value	Minimum	Maximum	Standard	Comment
methane_direct	digester_gas*Fraction_methan*662*(1-0.99)*1E-6	0.0371				[t/d],din
sludge_treatmen	sludge_recovery	540				[m3/d],

Inputs

Alias	Flow	Quantity	Amount	Unit	Tracked flows
sludge_recovery	Sludge for recovery [Waste for recovery]	Mass	5.4E005	kg	X

Outputs

Alias	Flow	Quantity	Amount	Unit	Tracked flows
sludge_recovery	sludge for treatment [Waste fo	Mass	5.4E005	kg	X
methane_direct	Methane [Organic emissions to	Mass	37.1	kg	

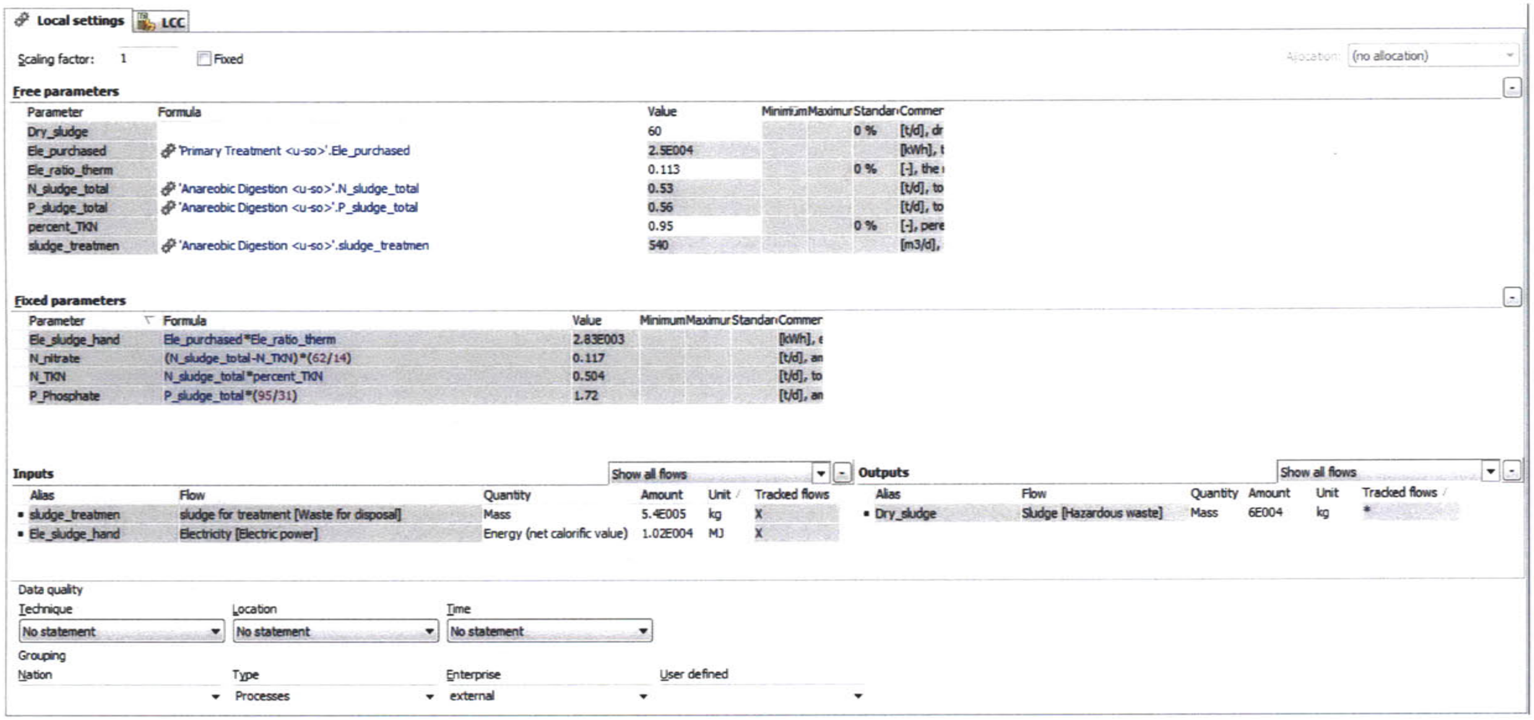
Data quality

Technique: No statement
Location: No statement
Time: No statement

Grouping

Nation:
Type: Processes
Enterprise: external
User defined:

Sludge Handling



Scaling factor: 1 ☐ Fixed

Allocation: (no allocation)

Free parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Dry_sludge		60			0 %	[t/d], dr
Ele_purchased	'Primary Treatment <u-so>'.Ele_purchased	2.5E004				[kWh], t
Ele_ratio_therm		0.113			0 %	[-], the
N_sludge_total	'Anareobic Digestion <u-so>'.N_sludge_total	0.53				[t/d], to
P_sludge_total	'Anareobic Digestion <u-so>'.P_sludge_total	0.56				[t/d], to
percent_TKN		0.95			0 %	[-], pere
sludge_treatmen	'Anareobic Digestion <u-so>'.sludge_treatmen	540				[m3/d],

Fixed parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Ele_sludge_hand	Ele_purchased*Ele_ratio_therm	2.83E003				[kWh], e
N_nitrate	(N_sludge_total-N_TKN)*(62/14)	0.117				[t/d], an
N_TKN	N_sludge_total*percent_TKN	0.504				[t/d], to
P_Phosphate	P_sludge_total*(95/31)	1.72				[t/d], an

Inputs Show all flows

Alias	Flow	Quantity	Amount	Unit	Tracked flows
sludge_treatmen	sludge for treatment [Waste for disposal]	Mass	5.4E005	kg	X
Ele_sludge_hand	Electricity [Electric power]	Energy (net calorific value)	1.02E004	MJ	X

Outputs Show all flows

Alias	Flow	Quantity	Amount	Unit	Tracked flows
Dry_sludge	Sludge [Hazardous waste]	Mass	6E004	kg	*

Data quality

Technique: No statement

Location: No statement

Time: No statement

Grouping

Nation:

Type: Processes

Enterprise: external

User defined: