Fachhochschule Köln
Cologne University of Applied Sciences

UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

FACULTADES DE CIENCIAS QUÍMICAS, INGENIERÍA Y MEDICINA

PROGRAMAS MULTIDISCIPLINARIOS DE POSGRADO EN CIENCIAS AMBIENTALES

AND

COLOGNE UNIVERSITY OF APPLIED SCIENCES

INSTITUTE FOR TECHNOLOGY AND RESOURCES MANAGEMENT IN THE TROPICS AND SUBTROPICS

LIFE CYCLE ASSESSMENT FOR WASTEWATER TREATMENT IN THE CHEMICAL INDUSTRY

THESIS TO OBTAIN THE DEGREE OF

MAESTRÍA EN CIENCIAS AMBIENTALES

DEGREE AWARDED BY

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MASTER OF SCIENCE

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IN THE SPECIALIZATION: RESOURCES MANAGEMENT

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COLOGNE, GERMANY AUGUST, 2012

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PROYECTO FINANCIADO POR:

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ABSTRACT

One of the environmental compartments that is most affected by the chemical industry activities is the hydrosphere. Consequently wastewater treatment systems have become an essential part of any industrial complex to minimize water contamination. Nevertheless, these systems consume energy and chemical reagents, while produce sludge and various emissions which represent distinct direct effects on the environment. It is necessary then to define a way to analyze these systems to determine their overall environmental impacts and be able afterwards to define the most environmentally optimal options.

In the present thesis a “gate to gate” life cycle assessment (LCA) methodology was applied to a wastewater purification system of a German large-size industrial site in order to evaluate the environmental impact of cleaning effluents through its life-cycle, considering various emissions and resources. Wastewater, taking into accounts its composition, has been considered the main input to the system.

According to the different steps of an LCA, this thesis starts with the description of the functional unit, and scope of the evaluation. The inventory analysis was later presented allocating the environmental burdens considering the influent composition. The impact assessment was then calculated using Umberto software to finally determine the wastewater treatment environmental profile. Additionally, it was made a comparison between the current process and a future modified one, where a sludge digestion phase is included.

Because the Currenta wastewater treatment plant resembles a multi-input/output scheme, special attention was put on the design an allocation model to define the Life Cycle Inventory (LCI). To achieve this, the environmental impacts that are caused by the consumption of ancillaries and energy carriers, the generation of sludge, and the emission of pollutants were partitioned to the wastewater composition by their specific cause. There were chosen Hydraulics (Q), Total Organic Carbon (TOC), Total Nitrogen (N), Total Phosphorus (P) and Hydrogen (H+) as main parameters to describe the wastewater composition.

By using the Life Cycle Assessment methodology and by tracing all processes involved in the Currenta wastewater treatment, it was found that the responsibility towards the environmental burdens is shared causally proportional by the wastewater inlet parameters. Furthermore it was shown that the future scenario where sludge digestion is included, even when it has major energy consumption, has a slightly better environmental performance than the current scheme.

RESUMEN

La hidrosfera es sin duda uno de los compartimientos ambientales que se ve más afectado por las actividades de la industria química; consecuentemente los sistemas de tratamiento de agua residual se han convertido en una parte esencial en cualquier complejo industrial para tratar de reducir al mínimo la contaminación del agua. Sin embargo estos sistemas consumen energía y otros materiales auxiliares, mientras que generan lodo y varias emisiones, teniendo éstos un efecto directo en el medio ambiente. Es entonces necesario encontrar la manera de analizar estos sistemas para determinar su impacto ambiental global y así luego poder definir cuales opciones son ambientalmente más óptimas.

En la presente tesis se aplicó la metodología de Análisis de Ciclo de Vida (ACV) "De la puerta a la puerta" a una depuradora de aguas residuales de un complejo industrial alemán. Esto para evaluar el impacto ambiental de limpiar efluentes a través de todo su ciclo de vida considerando varias emisiones y recursos. El agua residual, tomando en cuenta su composición, fue considerada como principal entrada del sistema.

De acuerdo a los diferentes pasos de un ACV, esta tesis empieza con la descripción de la unidad funcional y el alcance de la evaluación. Después es presentado el análisis de inventario asignando las cargas ambientales considerando la composición del afluente. Posteriormente la evaluación de impacto fue calculada usando el programa Umberto, para finalmente determinar el estado actual de la planta que permitan futuras mejoras. Adicionalmente, se realizó una comparación entre la actual configuración del proceso y otra modificada que incluye una fase extra de digestión de lodos.

La planta de tratamiento de aguas residuales de Currenta asemeja un esquema de entrada/salida múltiple. Por este motivo se puso especial atención en diseñar un modelo de asignación para definir el Inventario de Ciclo de Vida (ICV). Para lograr lo anterior los impactos ambientales, provocados por el consumo de auxiliares y energéticos, la generación de lodo, y la emisión de contaminantes, fueron particionados entre la composición del agua residual por su causa específica. Fueron elegidos como principales parámetros para describir dicha composición la hidráulica (Q), Carbón orgánico total (COT), Nitrógeno total (N), Fosforo total (P) e Hidrógeno (H+).

Usando la metodología de análisis de ciclo de vida y dándole seguimiento a todos los procesos involucrados en la planta de tratamiento de Currenta, se encontró que la responsabilidad hacia las cargas ambientales está repartida causalmente proporcional entre los parámetros de entrada del agua. También se encontró que el escenario futuro donde es incluida digestión de lodos, aun cuando consume más energía eléctrica, tiene un mejor rendimiento ambiental que el escenario actual.

ZUSAMMENFASSUNG

Eines der Umweltkompartimente am Meisten betroffen von den Aktivitäten der Chemieindustrie ist die Hydrosphäre. Um die Wasserverschmutzung auf ein Minimum zu reduzieren sind Abwassersysteme zu einem wesentlichen Bereich in jedem Industriekomplex geworden. Doch diese Systeme verbrauchen Energie und andere chemische Stoffe und erzeugen Schlamm und verschiedene Emissionen, welche wiederum einen direkten Einfluss auf die Umwelt haben. Deshalb ist es notwendig einen Weg zu bestimmen diese Systeme auf ihre Auswirkungen auf die Umwelt zu prüfen um anschließend in der Lage zu sein die umweltfreundlichsten Möglichkeiten zu bestimmen.

In der vorliegenden Arbeit wurde die Abwasserreinung eines großen deutschen Industrieunternehmens anhand der Methodik einer „Tor zu Tor" Ökobilanz (LCA) untersucht um die Umweltverträglichkeit verschiedener Reinigungsmittel während ihrer Lebensdauer im Hinblick auf verschiedene Emissionen und Ressourcen zu prüfen. Hierbei wurde Abwasser in seiner Zusammensetzung als Haupt-input betrachtet.

In Anbetracht unterschiedlicher Stufen einer Ökobilanz beginnt diese Arbeit mit der Beschreibung der funktionellen Einheit und dem Rahmen der Untersuchung zur Auswertung. Die später präsentierte Sachbilanz belegt die Umweltbelastungen unter Berücksichtigung der Abwasserzusammensetzung. Zur Feststellung des gegenwärtigen Stands der Kläranlage wurde eine Umweltverträglichkeitsprüfung mit der Umberto-Software (CML-Methode) vorgenommen um spätere Verbesserungen möglich zu machen. Zusätzlich wurde der derzeitige Arbeitsprozess mit einem künftig modifizierten Ablauf verglichen, der eine Phase der Schlammfaulung beinhaltet.

Da die Kläranlange von Currenta einer Multi-input/output-Anlage gleichkommt wurde besondere Aufmerksamkeit auf das Design eines Verteilungsmodells zur Bestimmung der Ökobilanz gelegt. Hierfür wurden die Umweltauswirkungen verursacht von Betriebsmittelverbrauch und Energieträgern, von Schlammerzeugung und Schadstoffemissionen nach ihrer spezifischen Wirkung auf die Abwasserzusammensetzung aufgeteilt. Hauptparameter zur Beschreibung der Abwasserzusammensetzung waren Hydraulik (Q), gesamtorganischer Kohlenstoff (TOC), Gesamtstickstoff (N), Gesamtphosphor (P) und Wasserstoff-Ionen (H).

Unter Nutzung der Methodik zur Ökobilanz und unter schrittweiser Verfolgung aller Prozesse die bei der Currenta Abwasseraufbereitung angewandt werden, wurde herausgefunden, dass die Abwasser-Input-Parameter sich proportional die Verantwortung für Umweltbelastungen teilen. . Es wurde außerdem deutlich, dass in einem zukünftigen Prozess unter Anwendung von Schlammfaulung ein geringfügig ökologisch besseres Ergebnis erzielt wird, obwohl ein höherer Energieverbrauch als im derzeitigen System damit verbunden wäre.

LIST OF ABBREVIATIONS AND SYMBOLS

General

ADP	Abiotic Depletion Potential
$A_{i,j}$	Element flow of the parameter i via the output j
$A_{i,w}$	Parameter flow of the element i in the average wastewater input
AP	Acidification Potential
b	Endogenous decay rate
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit
$B_{d,BOD}$	Daily BOD load
BOD	Biochemical Oxygen Demand
CB	Cascade Biology
cf_A	Consumption factor
CFC-11	Trichlorofluoromethane
CML	Center of Environmental Science, University of Leiden, The Netherlands
COD	Chemical Oxygen Demand
C_S	Liquid phase oxygen concentration in equilibrium with bulk gas phase
C_x	Lliquid phase bulk oxygen concentration (mg/l).
d	day
DALY	Disability-adjusted life years
DSP	Denitrifier sludge production
e^-	Electron
EP	Eutrophication Potential
Eq	Equivalent
FAO	Food and Agriculture Organization
FAETP	Freshwater aquatic Ecotoxicity potential
f_d	Active biomass fraction that is biodegradable
FSETP	Freshwater sediment Ecotoxicity potential
FU	Functional Unit
F_T	Temperature factor for endogenous respiration
GWP	Global Warming Potential
H	Hydrogen ion load
HSP	Heterotrophic sludge production
HTP	Human Toxicity Potential
ISO	International Organization for Standardization

K_La	Volumetric mass transfer rate coefficient
kg	Kilogram
kJ	Kilojoule
kWh	Kilowatt hour
l	Liter
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m^3	Cubic meter
N	Total Nitrogen
NSP	Nitrifiers sludge production
OC	Total oxygen needed in the aeration
OD	Odour Potential
$OV_{d,C}$	Daily consumption of oxygen for carbon elimination
$OV_{d,N}$	Daily consumption of oxygen for nitrification
$OV_{d,D}$	Daily saved consumption of O_2, which is covered by denitrification
P	Total Phosphorous
PAC	Polyaluminum chloride
p.e.	Person equivalent
Q	Wastewater Flow
S	Organic carbon concentration in the outflow
SETAC	Society of Environmental Toxicology and Chemistry
S^0	Organic carbon concentration in the inflow
$S_{NO3,D}$	Concentration of denitrified nitrate to nitrogen
$S_{NO3,in}$	Inlet Concentration of nitrate
$S_{NO3,out}$	Outlet Concentration of nitrate
TB	Tower Biology
$tc_{i,j}$	Transfer coefficient
TETP	Terrestrial toxicity potential
TKN^0	TKN concentration in the inlet
TOC	Total Organic Carbon
UNEP	United Nation Environmental Programme
VSS	Volatile Suspended Solids
WEF	Water Environment Federation
WE WW	Chempark wastewater
WU WW	Wupperverband wastewater

WW	Wastewater
WWTP	Wastewater treatment plant
Y	Yield Constant
$Y_{n(nit)}$	Nitrifier biomass synthesis yield
α	Correction factor
θ_x	Solid retention time

Chemical compounds

$AlPO_4$	Aluminum Phosphate
$C_5H_7O_2N$	Heterotrophic biomass
$Ca_{10}(PO_4)_6(OH)_2$	Calcium Hydroxyapatite
Ca(OH)2	Calcium Hydroxide
CaO	Quicklime/Calcium Oxide
CO	Carbon Monoxide
CO2	Carbon dioxide
DCB	1, 4 Dichlorobenzene
$FeCl_2$	Iron Chloride
$Fe_3(PO_4)_2$	Ferric Phospahte
H_2CO_3	Carbonic Acid
HCl	Hydrochloric acid
N_2	Nitrogen
N_2O	Denitrogen Monoxide
$Na_2Al_2O_4$	Sodium Aluminate
NaOH	Sodium Hydroxide
NH_3	Ammonia
NH_4	Ammonium
NO_2^-	Nitrite
NO_3	Nitrate
O_2	Oxygen
OH^-	Hydroxide ion
PO_4	Phosphate

CHAPTER 1.INTRODUCTION

This first chapter addresses some important points in introducing this research. Firstly, it contains an introduction to the study, then it states clearly the objectives of this research, subsequently roughly describes the methodology used in the study and finally it gives an overview of this thesis with regard to structure and presentation.

1.1 Introduction to the study

Chemistry has always played an important role in science and in our lives; however, historically it began to make a large scale impact on society during the industrial revolution in the 19th century, when chemical processes became an important agent to thrust most of the then young emerging industrial sectors. From this stage, chemistry began to evolve into the paramount industry responsible for the huge supply of abundant products that bring comfort into our lives today.

However, there has been a “hidden” cost involved. We all know and enjoy the benefits derived from the chemical process industry; unfortunately, altogether many harmful effects have been originated, for instance, dissolute consumption of large amounts of resources for a start, not to mention the release of abundant pollutant emissions due to destroy our delicate environment.

At the end of the 1960s, with the appearance paradigm-breaking writings (such as Rachel Carson’s Silent Spring) and the occurrence of many ecological accidents in which the chemical industry was involved, environmental concern started to emerge in the world. After a few years, the conscience and compromise of some industrialized countries were reflected in the definition of a very well know concept nowadays: “Sustainable development”. Sustainable development was defined by the Brundtland Commission in 1987 as the ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (UNEP, 2002).

Today, the challenge for the chemical industry is to continue to provide its usual benefits fulfilling the sustainable development definition. This is pursued, among other strategies, through the concept of environmental management which seeks pollution prevention in all environmental compartments (Muñoz, 2006).

One of the environmental compartments that is most affected by the chemical industry is the hydrosphere. Water pollution has contributed to rapid deterioration of the global ecological environment, and consequently is one of the main issues intended to be avoided by industry. Industrial water discharges can contain a wide range of contaminants and in many instances it not only drains directly into rivers and lakes, it also seeps into the ground contaminating aquifers and wells (UNEP, 2010).

Wastewater treatment systems have been designed and operated to control water pollution and minimize the environmental impacts of industrial and domestic wastewater discharge (Wu, et al., 2010), hence implementing the above mentioned sustainable development definition.

Nevertheless, wastewater treatment systems consume energy and chemical reagents, while producing sludge and a range of vicious emissions. Different wastewater treatment options available offer different performance characteristics, as well as distinct direct effects on the environment. These impacts exist in the entire life cycle of the treatment process. Thus, it is necessary to analyze the systems to determine their overall pollution and enable future improvements. (Wu et al, 2010).

System analysis is quite abstract; this is why tools are needed to transfer concepts into action and make environmental aspects more concrete. The Society of Environmental Toxicology and Chemistry (SETAC) has distinguished in this sense political instruments, procedural tools and analytical tools. The application of these tools provides consistent environmental information that facilitates adequate decision-making toward sustainable development. (Sonnemann, Castells, & Schuhmacher, 2004). Considering the assessment of environmental impact evaluation, some analytical tools like Life Cycle Assessment (LCA), Cost-benefit analysis, Material Flow Accounting, Environmental risk assessment, among others, usually offer the best option.

The German chemical industry as the number one in Europe and the fourth largest in the world (VCI, 2012) has its wastewater discharges treated with the best available technology are submitted to the highest standards (BMU, 2012). Within this context, an LCA of a chemical industry-processing wastewater treatment plant located in the Chempark of Leverkusen, Germany, was performed on the basis of both material and energy flows, with an exhaustive look into the overall feasibility in regard to their environmental impacts.

LCA offers the possibility of achieving objective and transparent decisions concerning environmental management. This allows the creation of new process development guidelines and the definition of environmental priorities taking into account the entire system (wastewater treatment in the current case) with respect to various emissions and resources (Köhler, 2006). For that reason and since it meets the aforementioned requirements in this introduction, LCA was chosen as the most adequate tool to be applied in the present work.

1.2 Objectives

The overall objective of this project is to generate information on the environmental life cycle of the CURRENTA wastewater treatment process advancing in the existing approaches of LCA methodology. By doing this was intended to estimate the ecological performance and environmental impacts of the treatment plant under study so its present status can be determined and therefore enable future improvements.

Recently in Currenta it has been proposed the project of implementing to the current plant design a sludge digestion process. This project will signify to the plant a considerable reduction in the biosolid disposal and the production of a profitable product (biogas) that will represent to the company additional earnings. This study also intends to compare the environmental burdens of the current system with those of this proposed project within the LCA context.

As a result of the mentioned above, the specific objectives of this thesis are as follows:

- To collect detailed flow operation data of CURRENTA WWTP that allows the elaboration of a complete LCI according to the process characteristics.

- To estimate an LCIA of the obtained LCI in order to calculate the ecological performance and environmental impacts of CURRENTA WWTP that can provide a basis for substantiated impact discussion and decision-making.

- To identify system hotspots with regard to environmental impacts to define priorities for process optimization.

- To set LCA tool as fix methodology in CURRENTA wastewater facility for further ecological evaluations.

- To make a comparison between current operation scenario and future planned scenario (sludge digestion) within the LCA context.

1.3 Methodology

Currenta operates three major treatment plants to depurate wastewater from various companies and production units at the CHEMPARK-sites Leverkusen, Dormagen and Krefeld-Uerdingen. The wastewater treatment plant in Leverkusen served as pilot case to adopt a “gate to gate” life cycle assessment (LCA) with methodology according to ISO14040 / 14044. In chapter 3 is given a detailed description of each phase of this methodology; however each step is listed below.

- Goal and Scope Definition
- Life Cycle Inventory Analysis
- Life Cycle Impact Assessment
- Interpretation

The methodology was carried out in an iterative process in which subsequent rounds achieved increasing levels of detail and led to changes in previous phases prompted by the results of a later one.

Main part of the thesis was the life cycle inventory (LCI), which was set up based on plant data collected, databases, open literature and qualified assumptions. Life cycle impact assessment (LCIA) was limited to keep the extent of the thesis acceptable.

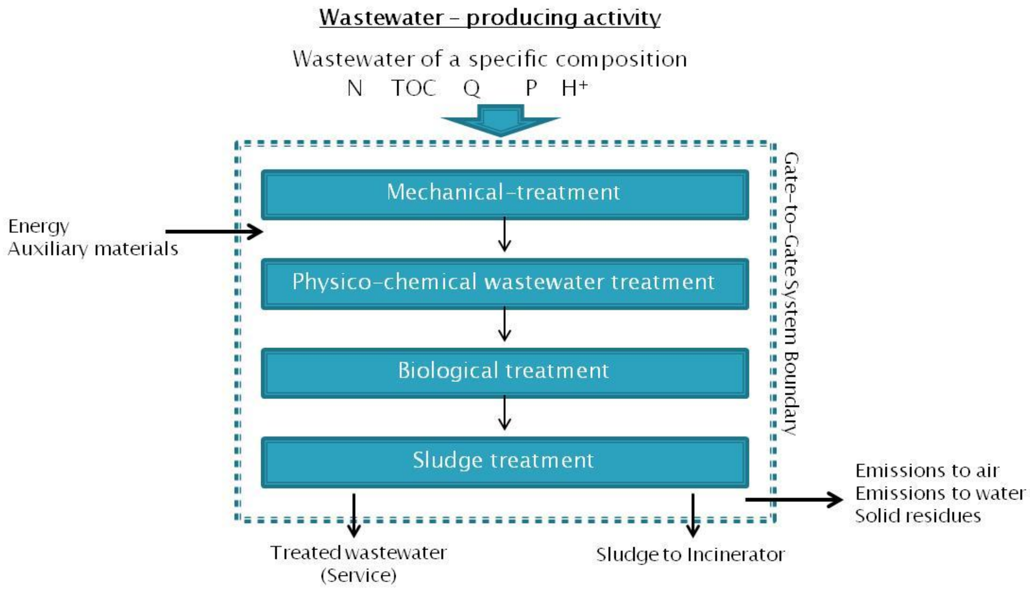

Figure 1. Gate-to gate system boundaries for CURRENTA wastewater treatment chain (adapted from Köhler, 2006)

The gate-to-gate system boundaries (Figure 1) included the wastewater treatment operations as a foreground system and the upstream system of the auxiliaries needs as background system. A rough consideration for the construction phase was done to make an approximated comparison with the foreground system. More detailed analysis in the construction was impossible because lack of data.

1.4 Thesis Outline

This master thesis is structured in 8 chapters. Chapter 2 and 3 constitute the conceptual framework of the study. From chapter 4 to chapter 6 the methodology is developed within the LCA context. Chapter 7 deals with the study conclusion and finally chapter 8 list the used bibliography.

After the introductory chapter 1, chapter 2 explains the state of the art of CURRENTA WWTP describing the flow diagram of the entire process. The study area (Leverkusen Chempark) and the responsible company (Currenta) are presented in this section.

Chapter 3 provides the background information of LCA methodology. General description of each phase according to ISO ISO14040 / 14044 is here defined. Additionally previous LCA studies applied in the wastewater field are also outlined.

Chapter 4 details the scope and goal definition of the study. Here are assigned the system boundaries and the functional unit of the analysis. Following is the Chapter 5 where the LCI model established is introduced. This is reported in relative numbers because the confidentiality agreements with Bayer/Currenta company.

Chapter 6 exposes the results of the research and provides an analysis of these results. Included in this chapter are the interpretations that can provide a readily understandable result of the LCA.

Chapter 7 is the concluding chapter and summarizes the findings of this research.

Finally at the end of the document are given all the references used during the present investigation.

CHAPTER 2. DESCRPTION OF THE WASTEWATER TREATMENT PLANT UNDER STUDY

The assessment carried out in this research was applied to CURRENTA Wastewater purification system; an industrial treatment plant located in Leverkusen, Germany. Here approximately 45 million cubic meters of wastewater coming from the industrial site Chempark and the nearby municipality is treated and discharged annually (CURRENTA, 2010). In this chapter, first a general overview of the site is presented; then a description of wastewater depuration system under study is given to provide reference information of the facility. As mentioned in chapter 1, one of the objectives of the present research is to make a comparison of the current WWTP operation with a future scenario that involves a modification in the sludge treatment stage. A description of this future scenario is included in the sludge treatment process part since is the only section of the system which would have significant changes.

The main aim of this part is to set a background of the wastewater treatment process of the case study to later on be able to make a complete inventory on basis of material and energy flows that can allow identify inputs, outputs and boundaries of the entire system.

2.1 Industrial Site

The so called industrial site "Chempark" is one of the biggest chemical parks in Germany. Many companies specializing in production, research and services are located there. Distributed in three sites; Leverkusen, Dormagen and Krefeld-Uerdingen, this site is the headquarters of the generation of an impressive range of products extended from basic and fine chemicals through to the manufacture and processing of polymers, active ingredients and other chemical products.

The present case study is focused in the Leverkusen site which is located close to the major Rhineland cities of Cologne and Dusseldorf. This 480-hectare site hosts companies from chemical and pharmaceutical industries to the high-tech sector (See Table 1). More than 5,000 chemicals are manufactured at Chempark Leverkusen, mainly nitration and chlorination products, aromatics, fine chemicals and silicon chemicals (CHEMPARK, 2012).

Is well known that water is one of the resources that is most consumed and affected by the chemical industry. CHEMPARK Leverkusen consumes approximately 240 million cubic meters of water each year. Around 95 percent of this is sourced either directly or indirectly from the River Rhine. To avoid major environmental damages and fulfill the current demanding regulations, in the Chempark are used highly effective methods to treat contaminated water (CURRENTA, 2010).

The company responsible of treating all the wastewater generated in the Chempark is the already mentioned previously in this chapter "Currenta". Currenta purification system treats only around ten percent of the water used in Chempark Leverkusen, corresponding to the part that actually comes into contact with products, being excluded the amount used for cooling purposes which is directly discharged to the river Rhine as uncontaminated wastewater. The contaminated effluent includes acidic, alkaline and organically loaded wastewater from the production facilities, laboratories and Technical Service Centers as well as sanitary and kitchen wastewater (CURRENTA, 2010).

COMPANY	PRODUCTION
Aliseca GmbH	Technical Services and Logistics
Bayer CropScience	Research
Chemion Logistik GmbH	Logistics solutions
Syntharo Fine Chemicals GmbH	Sale of fine and specialty chemicals
Impuls Fitness- und Gesundheitssport GmbH	Sport therapy services
KRONOS TITAN GmbH	Manufacturers of titanium dioxide and iron salts.
LANXESS AG	High quality chemicals, synthetic rubber, synthetic fibers and plastics
Pfaudler Werke GmbH	Provider of enameled reactor systems
	System and plant technology in enamel and other corrosion-resistant materials
polyMaterials AG	Monomer and polymer production
pronova BKK	Health insurance
Rheinische Pensionskasse VVaG	Pension fund
TANATEX Deutschland GmbH	Develops, produces and markets emulsifiers, antifoams and other specialties for non-textile use
Bayer HealthCare AG	Drugs and medical products
Momentive Performance Materials	Producer of silicones and silicone derivatives
	Products derived from quartz and advanced ceramics
Currenta GmbH & Co. OHG	Utilities, environmental services, safety and security, analytics, training and other CHEMPARK services.
WEBER	Fabrication, supply and installation of complete piping-systems, turn-around maintenance, as well as mechanized prefabrication.
Friedrich A. Kruse jun. Logistics Services & Co. KG	Specializes in storing and shipping hazardous substances
Tectrion GmbH	Maintenance
Ausbildungsinitiative Rheinland GmbH	Training programs
ELRO Rohrleitungsbau GmbH	Pipeline systems
Informium AG	Develops identification systems for paints and inks, coatings and packagings.
IBW Institut für Brandtechnologie GmbH	Offers fire safety research and development consultancy
Evonik Industries	Production plant for pyrogenic silica using as its raw materials chlorosilanes

Table 1. Main companies in Leverkusen Chempark (Chempark, 2012)

Additionally to the Industrial wastewater inflow and in agreement with Wupperverband (Water authorities from Wupper), it is also treated in CURRENTA WWTP municipal domestic wastewater coming from the surrounding communities (CURRENTA, 2009). Municipal and industrial wastewater streams are contrasting. Compared to municipal wastewater, industrial wastewater contains different pollutants and is often more variable, concentrated, and toxic (WEF, 2008). For this reason the nature of the process design and operation of Currenta WWTP where industrial and municipal wastewater is treated are also different depending on the type of water purified. Also is important to note that physical/chemical pre-treatment measures are carried out in the production plants themselves where the water is contaminated with substances that could impede biological treatment or that cannot be eliminated using biological methods (CURRENTA, 2010).

2.2 Wastewater treatment plant.

The evaluated wastewater treatment plant is operated, with some modifications through the years, since the beginning of the 70s (See Table 2). As mentioned before, industrial wastewater from the Chempark and municipal sewage from Wupperverband are biologically treated together to remove Organic matter, nitrogen and phosphorus. The design capacity is 1.75 million population equivalents (Kolisch, 2012). To give a rough overview of the process, a scheme of the plant is given in Figure 2. Wastewater flow diagram .

Start-up	1971: Basin biology 1980: Tower Biology 2005 - 2010: New construction of basin biology
Function	Treatment of wastewater containing organic loads
Capacity	Population equivalent of 1.7 million, of which CHEMPARK: 1.4 million p.e. Wupper water authority: 0.3 million p.e.
Wastewater volumes	CHEMPARK: 40,000 m³/d Wupper water authority: 60,000 m³/d Up to 195,000 m³/d in wet weather Bürrig: (sanitary, sludge pressing, rinse water from incineration plant, leachate): approx. 10,000 m³/d
Residence times	Total residence time of the wastewater in the treatment plant: approx. 2 – 3 days

Table 2. Wastewater plant summary (CURRENTA, 2010).

Composition	Units	Influent			Outlet
		WE	WU	Others*	
WW					
Flow (Q)	m^3/d	25.400	70.900	25.700	122.400
TOC	kg/d	16.700	6.900	4.600	3.300
COD	kg/d	55.000	18.000	-	7.100
N_{total}	kg/d	3.200	3.600	3.000	1.800
P_{total}	kg/d	660	360	-	71
$[H^+]$	kg/d	1.700	-	-	-
Sludge					
Flow (Q)	m^3/d	-	860	-	175
TS	t/d	-	10	-	70
Wasteair					
Flow (Q)	m^3/d	-	-	-	570.000
org C	mg/m^3	-	-	-	17

Table 3. Currenta WWTP daily average flows and concentration (Almanza, 2012).

***This category refers to the additional water that is that is fed after pretreatment coming from recirculation, rain run offs, sludge treatment plant, nearby wells (groundwater), WU bypass, and service water usage.**

2.2.1 Inflow

The inflow received by the WWTP is composed by two different gravity sewers. These channels flow approximately 10 meter underground from the Chempark in Leverkusen to the Currenta treatment plant. For both inlets there is a separate computing system that constantly monitors the stream fed to the facility. In the treatment plant, a coarse screen is used to remove larger materials from the wastewater (CURRENTA, 2009).

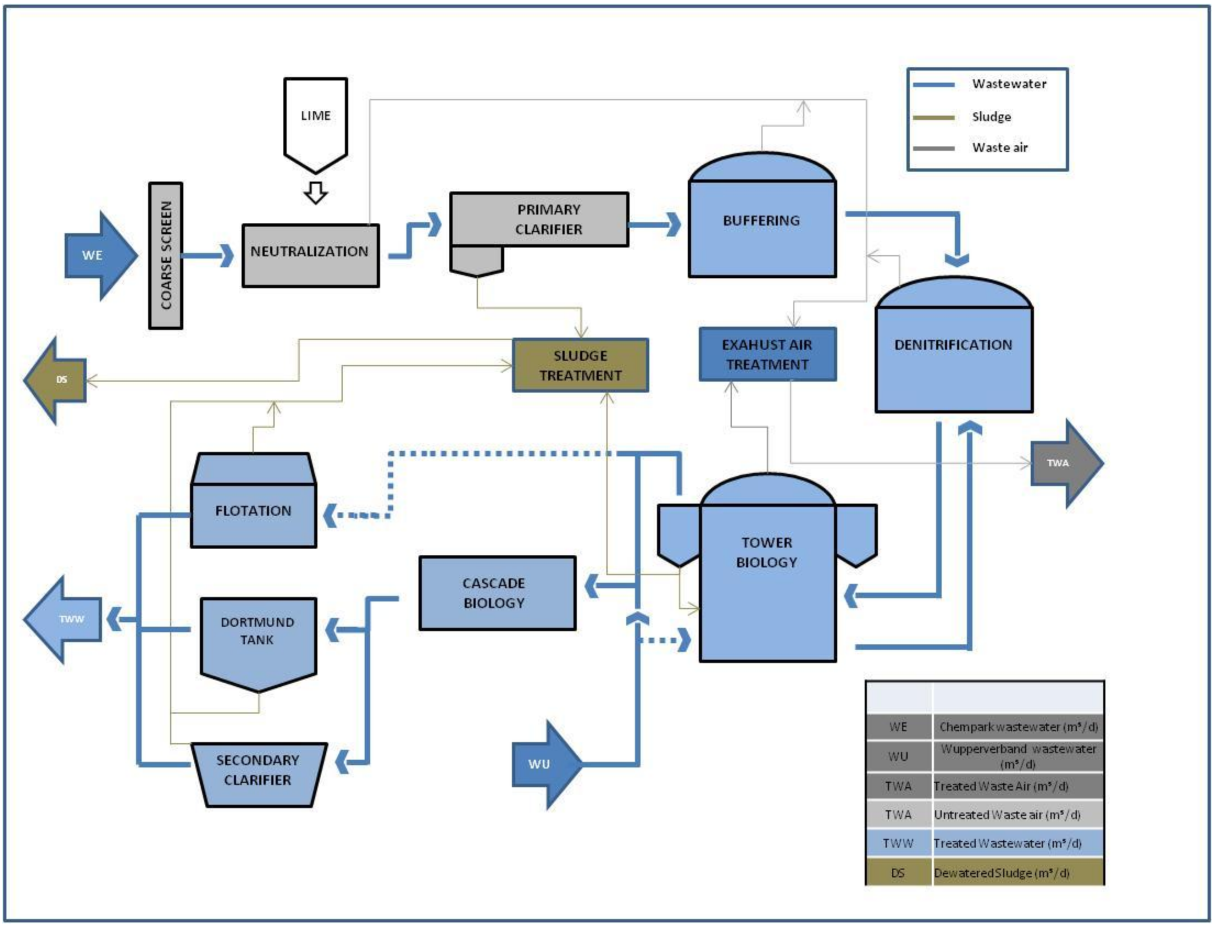

Figure 2. Wastewater flow diagram (CURRENTA, 2010).

2.2.2 Neutralization

Due to the nature of production, the wastewater is usually strongly acidic (pH value approx. 1.5). To protect the bacteria in the treatment plant, lime milk (fine white lime + water), is added as a neutralizing agent to the wastewater according to the pH level (CURRENTA, 2010).

There are 3 silos with a capacity available of 400 tons each that are used as intermediate storage of the powdered lime material received. For the preparation of the lime milk, it is made a suspension in the corresponding dissolving unit, of Calcium Oxide and water. Optimal solution concentrations of 18% lime/water are accomplished. Once the solution prepared it is stored in 2 distribution tanks (CURRENTA, 2009).

The neutralization step takes place in two parallel closed basins, each with 628 m^3 capacity, equipped with two mixers. To transport the waste water to the next step, primary clarification, it is pumped about 14 meters with the help of four centrifugal pumps delivered to the primary clarifiers (CURRENTA, 2009).

Consequence of the slow lime milk reaction with the acidic substances is the formation of precipitate (inorganic compounds and organic material as well), that later on in the next step is removed via settlement (Metcalf & Eddy, 2003). During these reactions, a large proportion of phosphate is also precipitated and separated along with the sludge.

2.2.3 Pre-clarification

In the next stage, pre-clarification, the precipitation products of the neutralization process and other solids sink to the bottom and are removed mechanically. Around 25 to 50% of the incoming biochemical oxygen demand, 50 to 70% of the total suspended solids (SS), and 65% of the oil and grease are removed during pre-clarification. Some organic nitrogen, organic phosphorus, and heavy metals associated with solids are also separated during primary sedimentation but colloidal and dissolved constituents are not affected (Pescod, 2012).

The primary treatment (Pre- Clarification) is composed by two groups of four primary sedimentation tanks. Each tank is 86 m long, 6 m wide and has an average depth of 2.5 m. So, the total volume of the pre-clarification system is 10 320 m^3 and the effective settling area is 4000m^2. The sludge removal is done with a scraper band. The entire clarification area is covered. The pre-clarified effluent passes through a collecting line to the pump sump, and then to the next stage (CURRENTA, 2009).

The resulting sludge in this stage is collected and pumped along with sludge from the other treatment stages and transferred to the sewage sludge treatment system (CURRENTA, 2010).

2.2.4 Buffering

In this stage the equalization of the wastewater quality is achieved. The objective is to reach the optimal buffer system for equalizing the flow-rates and contaminant concentrations of its outputs. So, the variable of incoming flow rate from the primary clarifiers can be balanced and the wastewater quality can be homogenized at different times. This improves the degradation performance in the subsequent biological treatment (WEF, 2008).

The mechanically pre-treated and neutralized wastewater from the Chempark is stored in 4 buffer tanks, which have a capacity of 2 x 25,000 m^3 and 2 x 10,000 (CURRENTA, 2009).

Furthermore, the Wupperverband wastewater coming from its previous mechanic treatment, has its own buffer tank of 15, 000 m^3, where it is stored before being fed to the cascade biology. It should be noted that the municipal wastewater is mechanically treated in a separate pre-treatment plant operated by Wupperverband using screens, grit chamber and settling tank. This part of the plant is designed for a maximum of 300,000 equivalents (CURRENTA, 2009).

2.2.5 Tower Biology

Secondary treatment is typically the most important part of the process, and is used primarily to remove the bulk of the suspended solids, organic materials (both hazardous and non-hazardous), and other soluble materials. In this case, the treatment applied is a biological one and takes place in two phases: First in the so called Tower Biology where is treated the high TOC concentrated effluent coming from the Chempark; and then the so called Cascade Biology where the clarified effluent from the Tower biology plus the wastewater coming from Wupperverband is together cleaned.

The Tower Biology is a high-rate, aerobic wastewater treatment system which requires up to 50 percent less land area for installation than conventional aeration systems and has an aeration process that minimize the quantity of off-gases. Since the reactor is completely enclosed, treatment of volatile organic chemicals (VOCs), odors and aerosols can be carried out in a controlled way to later on be treated if required (See Figure 3). The used air injectors ensure complete mixing of the process tank's contents without the need for any moving parts (Bayer, 2009).

There are 4 towers operating currently in the plant. Each tower has a capacity of 13 800 m^3, height and diameter is 26 m. They usually operate in two parallel lines: Tower 1+3; and Tower 2+4. There are also possible other configurations of operation. Sometimes only 3 towers are operated alternately when a tower is in maintenance. Also for example, in the period from March to late August 2010, the towers 2+4 were operated in series (Kolisch, 2012). The distribution of the wastewater / sludge mixture is carried out over 70 slot radiators which are evenly arranged at the bottom of each tank. The influent is fed to the towers by means of 10 pumps which transport the water from the previous stage (Denitrification tanks) (CURRENTA, 2009).

In order enhance the microbiological decomposition of the organic matter and the nitrification of the nitrogenous compounds air is needed (CURRENTA, 2010). Three bar compressed air is supplied to the tower biology system through a steel pipe delivered from the Chempark. Alternatively a 6 bar compressed air line, which can be reduced to 3 bar, is available (CURRENTA, 2009).

The BAYER Slot Injector is the main part of the BAYER Aeration System. The kinetic energy of the propelling water drags air into the injector, breaks the gas into small bubbles, and pushes the fine bubble water/ air dispersion into the activation tank (BAYER, 2009).

For the separation of wastewater/sludge mixture there are around each biotank concentrically disposed 16 intermediate clarifiers. The wastewater treated in the Tower Biology overflows to this clarifiers in which activated sludge and water are separated. The effluent is saturated with air; therefore the waste water must be degassed in a cyclone before entering the sedimentation tank. The clear effluent flows by gravity into the cascade biology. Most of the activated sludge is fed back into the towers using centrifugal pumps. A smaller amount is removed as excess sludge and passed to the sludge treatment system (CURRENTA, 2009).

Phosphorus removal is achieved in this stage by adding aluminum salts that later on precipitate with the sludge in the intermediate clarifiers (CURRENTA, 2010).

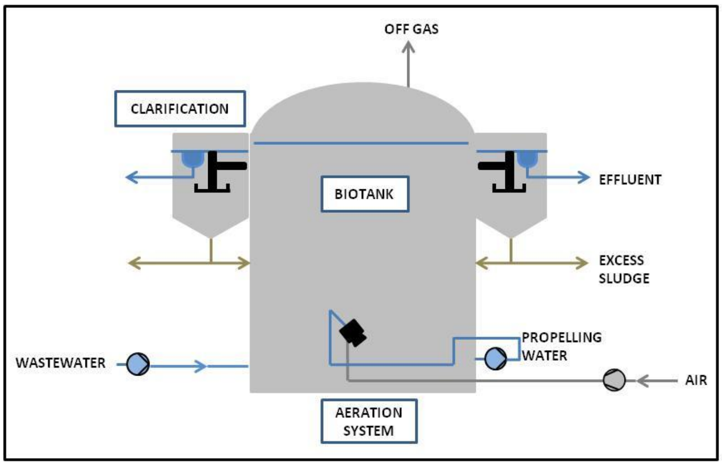

Figure 3. Tower biology diagram (Bayer, 2009)

2.2.6 Denitrification

To be able to eliminate nitrogenous molecules such as ammonium compounds, further strains of bacteria are required in addition to those already used to break down carbon compounds. In an initial stage, nitrifying bacteria use oxygen to convert the ammonium compounds into nitrate. In an upstream process, this nitrate is transformed into molecular nitrogen and passes into the ambient air (Denitrification tanks) (CURRENTA, 2010).

As this process can only be carried out in the absence of oxygen (anoxia) and in the presence of carbon compounds, 80 percent of the wastewater flowing out of the towers is pumped into a separate tank. This tank contains very little atmospheric oxygen and ample carbon compounds sourced from the untreated site wastewater that flows through the tank before being fed into the towers (CURRENTA, 2010).

For this stage of the process there is a denitrification tank (10,000 m^3) for each 2 Biology Towers connected, in where takes place via a recirculation ratio of at least 200%, the reduction of the previously formed nitrates, and therefore can be achieved the nitrogen elimination (CURRENTA, 2009).

2.2.7 Flotation

In order to be able to accept the contractually agreed amount of wastewater from the municipal area, a partial quantity of the tower biology outflow can be discharged directly into the receiving water before the cascade biology. To do this, it is necessary to pass the water through two flotation cells before. With this, the capacity for municipal wastewater increases in the cascade biology (CURRENTA, 2009).

The process that takes place in the cells mentioned above is called flotation and consists in attaching gas bubbles to the flakes of sludge in the wastewater. As they are less dense than the substance around them, they then rise to the surface of the liquid and form a foam layer, or flotate, which is then removed. This attachment is enhanced by the addition of a synthetic polymer. The sludge generated here is gathered and pumped along with sludge from the other treatment stages and transferred to the sewage sludge treatment system (CURRENTA, 2009).

2.2.8 Cascade biology

The water produced from the Tower Biology, which is not sent directly to the flotation cells, flows along with the municipal wastewater to continue its purification in the cascade biology. This is carried out in 4 open activated sludge tanks as a second biological process stage that together have a total volume of 36 840 m^3 (= 4 x 9.210 m^3). Four turbo blowers are responsible for adding the oxygen and the mixing (CURRENTA, 2009).

The biology is designed as a cascade activation which allows nitrification-denitrification processes. Each cascade is composed of four chambers, which alternate aerobic and anoxic conditions to achieve biological Nitrogen removal (Diering, 2005).

The activated sludge produced in the Cascade Biology is separated in five secondary clarifiers (25.544 m^3) and ten Dortmund tanks (25.544 m^3). The treated wastewater stream is discharged via a common line into the Rhine under online supervision. The excess sludge from the secondary clarification is fed into the sewage sludge treatment system. Phosphorus removal is achieved in this stage by adding iron salts that later on precipitate with the sludge (CURRENTA, 2009).

2.2.9 Waste air treatment

The extracted air from the neutralization stage and the respiratory air from the buffering tank are deodorized thermally together with the exhaust air from the tower biology. The system consists of three combustion chambers that can be operated alternately so all the waste air is always burned (up to 60 000 m^3 / h). This thermal treatment works at 800°C with natural gas as fuel. Organic substances contained in the exhaust air are oxidatively broken and then converted to inorganic substances. Two measuring devices are installed to detect the C content in the waste air constantly (CURRENTA, 2009).

2.2.10 Sludge treatment

2.2.10.1 Current process

The sewage sludge generated in the plant (industrial and municipal pre-clarification sludge and surplus sludge) is concentered, equalized and de-watered using 9 membrane filter presses and by the addition of polymer, irons salts and lime (CURRENTA, 2010). Solids must be thickened (concentrated) and dewatered to comply with environmental regulations and minimize the volume to be disposed. Minimizing solids volume mostly helps to control disposal costs. Thickening and dewatering are sequential processes: solids are thickened before dewatering because dewatering systems typically perform better if their influent contains more than 5% solids. (WEF, 2008)

The filter cake is burned in an incinerator on the same site. The ash and unburned filter cake that is left after incineration is deposited at the landfill site (CURRENTA, 2010).

Acidic water from the air scrubbers of the incinerator are neutralized together with the filter dust in a separate washing water treatment plant. The resultant solid material can be drained by two chamber filter presses. The resultant filter cake is deposited directly on the plant's own landfill (CURRENTA, 2009).

2.2.10.2 Future scenario

In contrast with the current process, in the future scenario before the thickened/dewatering stage, the sewage sludge undergoes to an anaerobic digestion. This digestion allows the reduction and stabilization of the organic solids. Additionally anaerobic digestion produces energy in the form of biogas, improves of dewaterability and let achieve a high quality final product (Blöcher, 2011).

Anaerobic digestion is a biological process involving the breakdown of organic matter by methanogenic bacteria consortia in absence of oxygen. The main reaction in this biochemical process are hydrolysis, acid formation and methane formation (Rittman & McCarty, 2001).The biogas produced is composed up on its majority of methane (CH_4) and carbon dioxide (CO_2) (60- 40 % approx.), and other gases such as hydrogen present in less amounts (Zatarin, 2011).

The digested sludge then would be thickened and dewatered (centrifuges planned instead of filter presses) before being burned in Currenta incinerator.

Here is important to note that, because the prior digestion, the quality of the supernatant from sludge thickening and dewatering would contain high concentrations of solids, organic matter, ammonia nitrogen and other compounds. This supernatant would be fed back to be treated in the tower biology stage, what would represent an increase in the quality parameters of the TB inflow.

In Figure 4 is given the general flow diagram of the planned anaerobic sludge digestion stage.

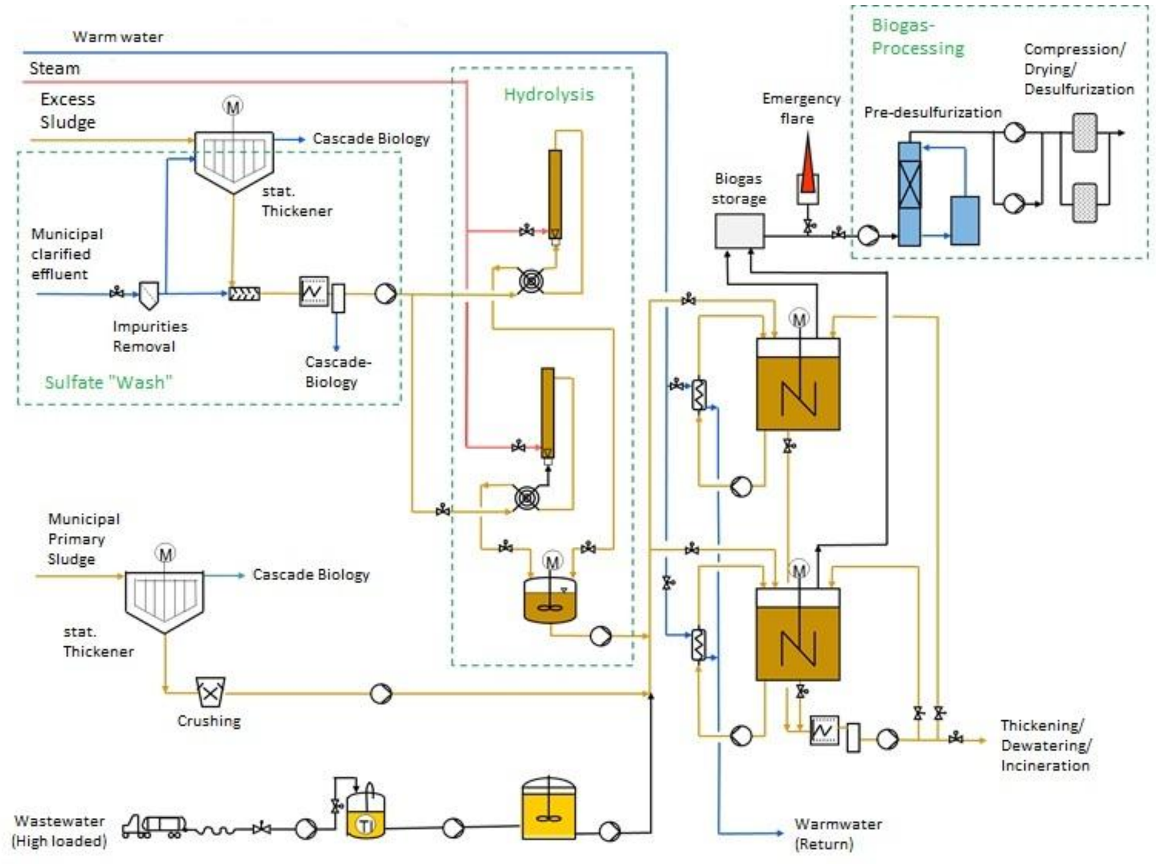

Figure 4. General flow diagram of the planned Anaerobic sludge digestion stage (Blöcher, 2011)

2.3 Effluent Quality

The approximately 45 million cubic meters of wastewater treated are discharged annually into the Rhine under constantly online supervision. When reaching the river, the levels of organic matter (TOC) in the treated wastewater are reduced by approximately 90%. Besides, nitrogen and phosphorus levels are reduced by 80% and 95% respectively. The remaining levels are achieved to the 100% through the Rhine resilience capacity (Almanza, 2012). In all cases, the concentration values are below the limits established by the German Wastewater directive, which is the responsible of treatment standards and emissions limitations in Germany (Deutsche Bundesregierung, 2004). For comparison with the sludge digestion future scenario, the same influent and effluent quantity and quality that the current scheme was considered.

CHAPTER 3. LIFE CYCLE ASSESSMENT GENERALITIES

As described earlier in the methodology, LCA was the chosen tool in the present research to carry out the environmental assessment of the WWTP under study. The objective of this chapter is to give an overview of this tool defining briefly some important concepts and practical applications of the methodology. Within the practical applications is included a literature review of previous research related with different options for wastewater treatment.

3.1. Conceptual Framework

Life-cycle assessment (LCA) of a product, process or activity encompasses the evaluation of the environmental effects produced during its entire life-cycle, from its origin as a raw material until its end, usually as a waste. According to ISO it is defined as “the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO, 2006). This definition goes further the limited approach where only the manufacturing step was recognized as the pollution driver. Several purposes can be fulfilled with this kind of methodology: Comparison of alternative products, processes or services; comparison of alternative life cycles for a certain product or service; or identification of parts of the life cycle where the greatest improvements can be made (Roy, et al., 2009).

The international standard ISO 14040 establishes principles universally valid for LCA. These principles are fundamental and should be used as guidance for decisions relating to both the planning and the conducting of a LCA (ISO, 2006). From this guidance comes the structure of a LCA study which comprises 4 phases: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. The relationship between the phases is illustrated in Figure 5.

These four phases are distributed within ISO along patterns: ISO14040 (2006) provides the general framework for an LCA. ISO 14041 (1998) provides guidance for determining the goal and scope of an LCA study and for conducting a lifecycle inventory (LCI). ISO 14042 (2000) deals with the life-cycle impact assessment (LCIA) step and ISO 14043 (2002) provides statements for the interpretation of results produced by an LCA. Moreover, technical guidelines illustrate how to apply the standards (Sonnemann, Castells, & Schuhmacher, 2004).

It must be noted that an LCA is not necessarily carried out in a single sequence. It is an iterative process in which subsequent rounds can achieve increasing levels of detail (from screening LCA to full LCA) or lead to changes in the first phase prompted by the results of the last phase (Sonnemann, Castells, & Schuhmacher, 2004). In the next lines are described briefly each of these different LCA steps.

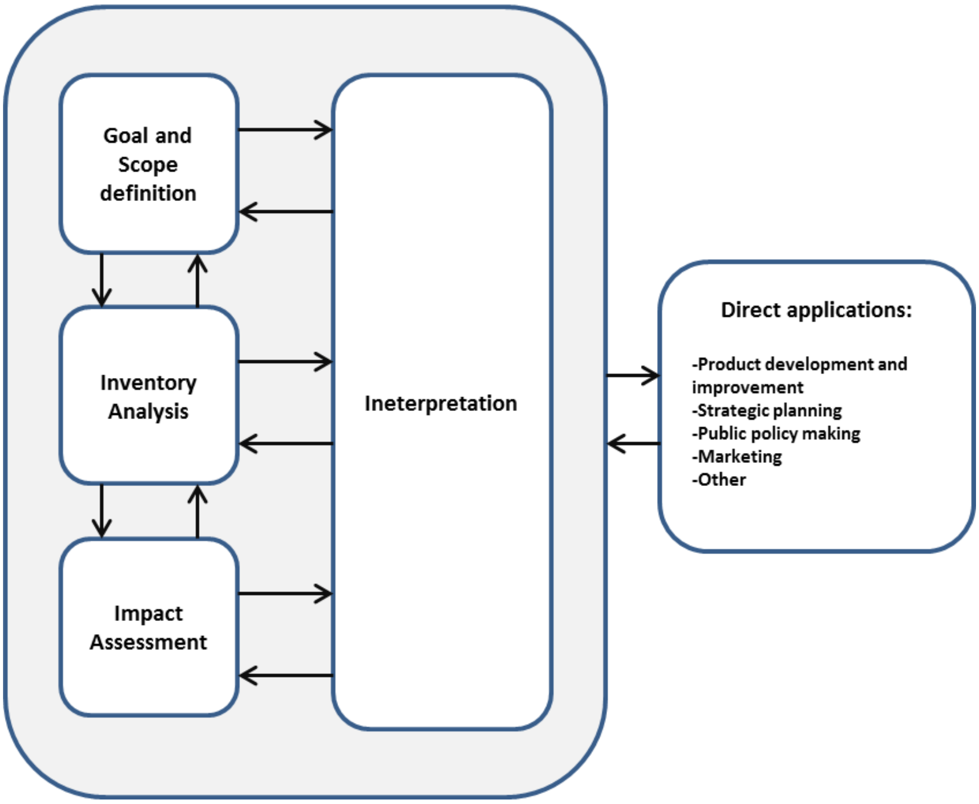

Figure 5. Schematic LCA framework (ISO, 2006)

3.1.1. Goal and Scope Definition

The first and probably most important step of a LCA is the Goal and Scope definition. This because here is defined the reason to make the assessment. The questions to be answered here will lay the basis of the rest of the study and define the purpose of the study, the expected product of the study, system boundaries, functional unit (FU) and assumptions (Roy, et al., 2009).

The system boundaries of a system are illustrated by a general input and output flow diagram. All operations that contribute to the life cycle of the product, process, or activity fall within the system boundaries (Roy, et al., 2009). In setting the system boundaries, it is useful to distinguish between `foreground' and background systems. The foreground system is defined as the set of processes directly affected by the study delivering a functional unit specified in Goal and Scope Definition. The background system is that which supplies energy and materials to the foreground system, usually via a homogeneous market so that individual plants and operations cannot be identified (upstream processes) (Azapagic, 1999).

The system function is also specified within Goal Definition and Scoping and it is expressed in terms of the functional unit(s) as a measure of the function(s) that the system delivers (Azapagic, 1999). This unit is used as a basis for calculation and usually also as a basis for comparison between different systems fulfilling the same function. The purpose of FU is to provide a reference unit to which the inventory data are normalized. The definition of FU depends on the environmental impact category and aims of the investigation. The functional unit is often based on the mass of the product under study (Roy, et al., 2009).

3.1.2. Life Cycle Inventory Analysis

The inventory analysis collects all the data of the unit processes within a product system and relates them to the functional unit of the study. Here all the environmental loads or environmental effects generated by a product or activity during its life-cycle are identified and evaluated. Environmental loads are defined here as the amount of substances, radiation, noises or vibrations emitted to or removed from the surroundings that cause potential or actual harmful effects (Sonnemann, Castells, & Schuhmacher, 2004). This phase is the most work intensive and time consuming compared to other phases in an LCA, mainly because of data collection. The data collection can be less time consuming if good databases are available and if customers and suppliers are willing to help (Roy, et al., 2009). The data collection can be built on from different kinds of data sources, which include site specific data (taken in site) and already existing commercial databases that provide information for processes that are not product specific. Many LCA databases exist and can normally be bought together with LCA software.

Special consideration in this phase requires multifunction processes, which are defined as activities that fulfill more than one function (production process with more than one product). An example of this case is a waste management process dealing with more than one waste flow (Wastewater treatment, incinerators). Here the problem is to decide what share of the environmental load of the activity should be assigned to the product investigated (Ekvall & Finnveden, 2001). In cases like this, an allocation strategy, which describes partitioning of the input and output flows of the unit process to the different product or functions under study, is needed (ISO, 2006).

There are two general ways to deal with the allocation problem: it can either be avoided by expanding system boundaries or disaggregating the system, or solved by using a method based on the real behavior of the product system (causal relationships) (Azapagic & Clift, 1999). It is difficult to define general rules for environmental load allocation because of the variety of options; sometimes different criteria can be used for the same process. Each practitioner shall define his own allocation model depending of the specific case.

3.1.3. Life Cycle Impact Assessment

The life-cycle inventory offers product-related environmental information consisting basically of a quantified list of environmental loads (raw material consumption, air and water emissions, wastes, etc.) that give the amount of pollutants to be assigned to the product. However, the environmental damage associated with them is not yet known (Sonnemann, Castells, & Schuhmacher, 2004). LCIA makes the results from the inventory analysis more understandable and more manageable in relation to human health, the availability of resources, and the natural environment. According to the ISO principles the impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts using the LCI results (Figure 6) (ISO, 2006). This phase aims to understand and evaluate environmental impacts based on the inventory analysis, within the framework of the goal and scope of the study. Here, the inventory results are assigned to different impact categories, based on the expected types of impacts on the environment. (Roy, et al., 2009).

The general framework of the LCIA comprises several mandatory elements that convert life-cycle inventory results into indicator results; in other words, it consists of aggregating and identifying the environmental burdens quantified in the inventory analysis, into environmental impact categories (Jacquemin, Pontalier, & Sablayrolles, 2011). An impact category is defined as a class representing environmental issues of concern. Udo de Haes (1996) provides a default list of impact categories in LCA (see Table 4). The list is not meant as a minimum and neither as a maximum list. (Potting, et al., 2001)

LCIA is generally conformed by classification, characterization, normalization and valuation (Sonnemann, Castells, & Schuhmacher, 2004). In addition, there are optional elements for normalization, grouping or weighting of the indicator results and data quality analysis techniques (ISO, 2006).

Classification is the assignment of the LCI results to the impact categories selected. Characterization is the assessment of the magnitude of potential impacts of each inventory flow into its corresponding environmental impact. Characterization provides a way to directly compare the LCI results within each category. Normalization expresses potential impacts in ways that can be compared (e.g., comparing the global warming impact of carbon dioxide and methane for the two options). Valuation is the assessment of the relative importance of environmental burdens identified in the classification, characterization, and normalization stages by assigning them weighting which allows them to be compared or aggregated. Impact categories include global effects (global warming, ozone depletion, etc.); regional effects (acidification, eutrophication, etc.); and local effects (nuisance, effects of hazardous waste, effects of solid waste, etc.) (Roy, et al., 2009). In Figure 7 is possible to the elements of the LCIA.

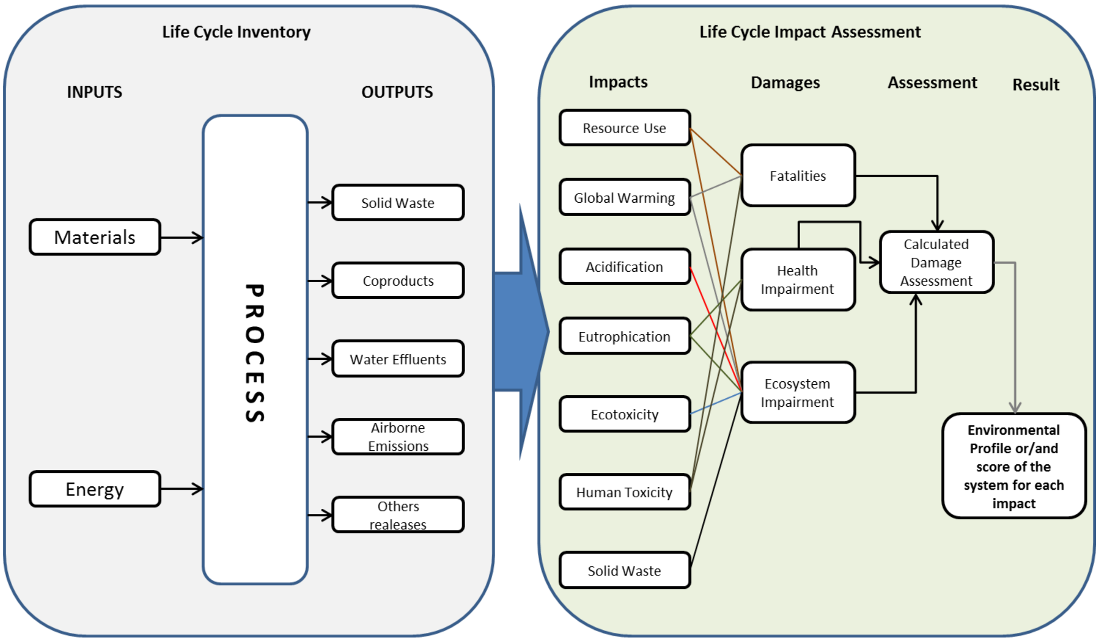

Figure 6. LCA Overview (Friedrich, 2001)

Impact categories	Possible indicator
Input-related categories	
Extraction of abiotic resources	Resource depletion rate
Extraction of biotic resources	Replenishment rate
Output-related categories	
Climate change	kg CO_2 as equivalence unit for GWP
Stratospheric ozone depletion	kg CFC-11 as equivalence unit for ODP
Human toxicity	HTP
Eco-toxicity	Aquatic eco-toxicity potential (AETP)
Photo-oxidant formation	kg ethene as equivalence unit for photochemical ozone creation potential (POCP)
Acidification	Release of H^+ as equivalence unit for AP
Nutrification	Stoichiometric sum of macronutrients as equivalence unit for the nutrification potential (NP)

Table 4. Impact Categories and Possible Indicators proposed by Udo de Haes , et at (Sonnemann, Castells, & Schuhmacher, 2004).

Many LCA commercial tools in the market can help to carry out full LCAs of a big variety of systems and products; and within the packages are included different methodologies that have been developed for LCIA over the years: EDIP97, Ecoindicator 99, CML 2001 , IMPACT 2002+, etc. into which life-cycle inventory results may be assigned (Jacquemin, Pontalier, & Sablayrolles, 2011).

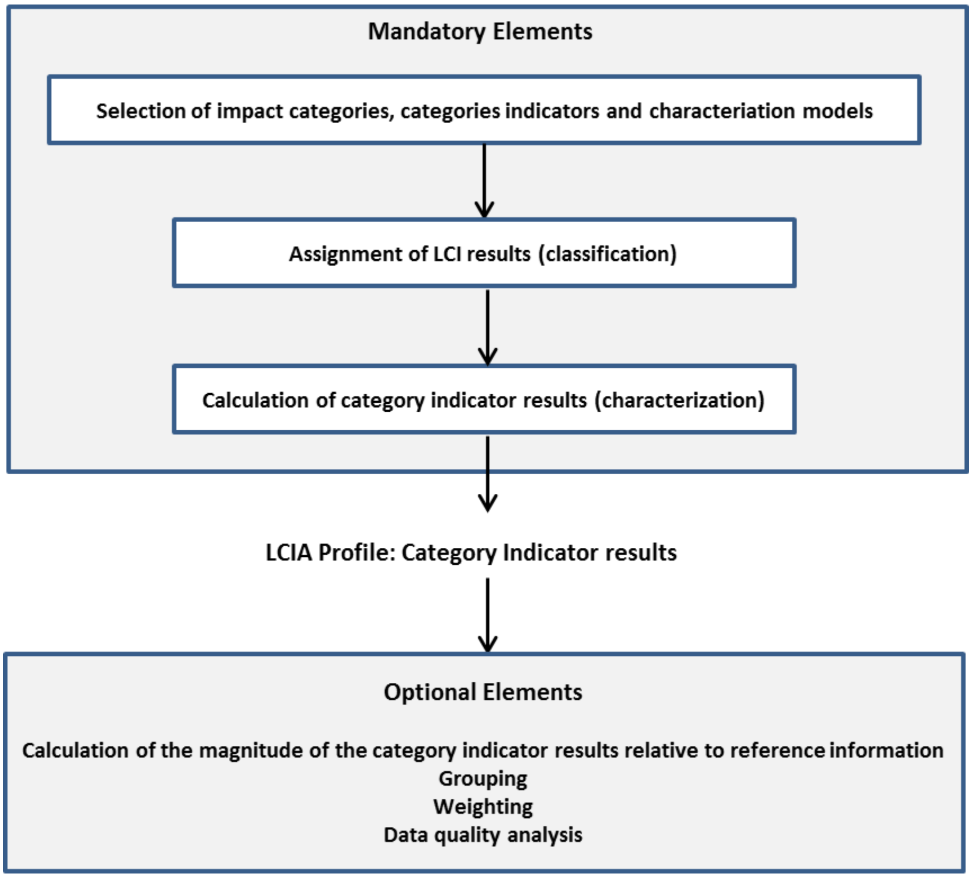

Figure 7. Elements of the LCIA phase (ISO, 2006)

3.1.4. Interpretation

Interpretation is the last phase in LCA where final evaluation is made. The purpose here is to draw conclusions that can support a decision or can provide a readily understandable result of the LCA. The inventory and impact assessment results are discussed together and significant environmental issues are identified for conclusions and recommendations consistent with the goal and scope of the study. Interpretation results to be a systematic technique to identify and quantify, check and evaluate information from the results of the LCI and LCIA, and communicate them effectively. This assessment may include both quantitative and qualitative measures of improvement, such as changes in product, process and activity design; raw material use, industrial processing, consumer use and waste management (Roy, et al., 2009). The results of the interpretation may lead to a new iteration round of the study, including a possible adjustment of the original goal. Concluding/recommending and reviewing/revising should preferably be based on uncertainty and sensitivity analysis (Potting, et al., 2001).

3.2. Previous research on Wastewater Treatment

Initially LCA was used mainly to be applied to make products comparisons for consumer and policy purposes. Nevertheless, nowadays this methodology has become versatile and consequently used in many contexts which include integrated applications in environmental assessments in the evaluation of numerous kinds of processes. In this manner, LCA is now an option of systems analysis for quantifying industrial process by identifying flows which are major contributors to environmental loads (Wu, et al., 2010). This is important to recognize operation hotspots that can be set as areas for improvement which will have the greatest influence on total life cycle impacts (Burgess & Brennan, 2001)

LCA has already been applied in previous research to analyze the environmental impacts of different wastewater treatment plant including both industrial and municipal facilities. This is particularly challenging, because of the difficulty of properly delimiting the system boundaries, and because of the difficulty of considering wastewater composition (Barjoveanu, Comandaru, & Teodosiu, 2010). Different options of wastewater treatment have different performance characteristics, as well as distinct direct effects on the environment which may occur at various steps in a WWTP's lifecycle. In the following an overview of relevant studies is briefly described mainly to generate a notion of LCA application in the Wastewater treatment field.

One of the first studies regarding wastewater was done by Emmerson et al in 1995 (Emmerson, Morse, Lester, & Edge, 1995). Here, they investigated a British small-scale sewage treatment plant by using LCA. Interestingly, because in other related studies is not done so, they included within the system boundaries beside the operation stage of the plant, its construction and dismantling. This enabled a comparison between process options, and the identification of opportunities for the improvement of environmental performance. They concluded that operational energy is one of the important contributors in the overall life cycle of the plant and that the operation stage has the highest contribution. Unfortunately, because it was one of the first studies about wastewater, methodologies used by Emmerson are very different and because of that comparisons of results are limited and even impossible with current LCAs.

In 2000, Lundin and collaborators applied LCA to conventional wastewater systems in Sweden, to later on compare to different source separation systems. Attention was given to material and energy use, while emissions to water were limited to include only oxygen-demanding substances and suspended solids, neglecting emissions of phosphorus and nitrogen. The functional unit used in this analysis was treatment of one yearly person equivalent of sewage (per year). It was concluded that the operational electricity requirements per person equivalent were considerably lower for the large-scale systems than for the small-scale ones; although no such benefits were found for fossil energy and related atmospheric emissions. It was also demonstrated that some of the most important environmental advantages of separation systems emerge only when models of wastewater systems are expanded to also include potential effects on the production of fertilizers (Lundin, Bengtsson, & Molander, 2000)

Other authors (Hospido, Moreira, & Feijoo, 2008) designed their analysis to evaluate the environmental impacts corresponding to 4 municipal wastewater treatment plants with primary and secondary treatment. The treatment of the wastewater generated from one person equivalent (pe) was established here as functional unit. Systems boundaries were limited to the operation stage because they aimed the comparison of different technical options just at the plant level. The differences presented among the facilities on their configurations allowed their comparison and the definition of the less environmentally damaging scheme for the treatment of this type of wastewater.

Similar approach to the present study was presented by Köhler in her PhD dissertation in 2006. Here, as part of her study, it was applied a LCA considering the industrial wastewater process under study as a multi input/output system. She presented a modular gate to gate inventory model which enabled the calculation of inventory parameters as a function of the wastewater composition and the technologies applied (Köhler, 2006). The comparison of the results of the current study with those of Köhler´s is limited due to the different objectives and methodologies and also due to the fact that different processes were investigated. However, how the system was addressed and functional unit defined, allowed to use for the present thesis similar basis to define the inventory model. Similar than Köhler other studies exist where multi input/output concepts were presented in the models and consequently also served as support for the current work (Doka, 2009) (Seyler, Hofstetter, & Hungerbühler, 2005) .

3.3. LCA limitations

LCA is considered nowadays a very important tool in environmental management because it offers objectively results that allow a better decision making. However, despite its many advantages it also has limitations which have to be considered when this tool is applied. Its holistic nature for example, in addition of its main strength is also its main limitation, since the broad scope of analyzing the entire life cycle of products and processes can only be achieved at the expense of simplifying other aspects (Muñoz, 2006) . In the following table are summarized some of the particular limitations that a LCA can present.

Particular LCA limitations
° LCA addresses potential rather than actual impacts
° LCA doesnt include Market mechanisms or other secondary effects on technological development.
° LCA generally regards all processes as linear, both in the economy and the environment.
° LCA focuses on environmental issues associated to products and processes, excluding economic and social consequences.
° Availability of data

Table 5. LCA limitations summary (Muñoz, 2006)

Specifically, in wastewater treatment application field, there are engaged multitude of methodologies, impact categories and site specific assumptions that make study comparison and correlations almost impossible. Furthermore, LCA has been reported as a very complex and time consuming methodology, that does not always account for all the environmental impact and to a far lesser extent the economic impacts of various wastewater treatment alternatives (Barjoveanu, Comandaru, & Teodosiu, 2010)

In conclusion, LCA has a series of shortcomings and limitations, most notably related to data gaps, data quality and value-choices (Friedrich, 2001). Depending on the case and if it is needed, LCA has to be complemented with other environmental analytical tools to fill those gaps caused by its limitations (Muñoz, 2006). Also is important to mention, that in the interpretation LCA phase has to be specified and explained the known particular limitations of the entire analysis.

CHAPTER 4. GOAL AND SCOPE DEFINITION OF THE STUDY

According to the ISO standards, the goal and scope of the study must be clearly defined. The goal of an LCA states the reasons for carrying out the study and the intended audience, i.e. to whom the results of the study are intended to be communicated. The scope determined by the research objectives and should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal (ISO, 2006). In this chapter, both goal and scope are defined to set the basis of the rest of the thesis.

4.1. Purpose of the study

In this case study, the LCA methodology is applied to the Wastewater purification in an industrial large-size German plant (Leverkusen Chempark) in order to evaluate the environmental impact of cleaning effluents through the entire life-cycle. The goal of the study (as presented in Chapter 1) is to generate information on the environmental life cycle of the CURRENTA wastewater treatment process advancing in the existing approaches of LCA methodology. This with the aim of identifying system hotspots to define priorities for process optimization, and to set LCA tool as fix methodology in CURRENTA wastewater facility for further ecological evaluations.

The intended audience or the target group for this study is conformed of industry-internal personal: Decision makers (environmental and operational managers), engineers involved in designing new wastewater works, scientists involved in the development WWT technology, and environmental planners. Still, LCA practitioners are expected to consider this study for methodology comparison intentions.

Therefore, in general terms, the purpose of the present LCA is to analyze the environmental performance of Currenta's Wastewater treatment process to determine its present status and to enable future improvements. Also it is pretended to make a comparison between the current process design of the treatment process and a future modified one, where a sludge digestion phase is included.

To achieve the aims set forth herein, the LCA study must be organized by carefully dividing the manufacturing process into well-defined sections or phases, to identify afterwards which parts of the process are responsible for each environmental effect.

4.2. System boundaries

The system under study is the wastewater depuration of the effluent coming from the Leverkusen industrial site Chempark and the nearby municipality. The treatment system has been fully described in Chapter 2.

A “gate to gate” system is considered; this means that the system starts when the water is received from the industrial site in the collecting channels to feed the plant and ends with the treated wastewater discharge to the river Rheine. In an intermediate point it is also fed municipal wastewater from the Water authorities from Wupper. The generation of sludge was considered till it is thickened and dewatered in the sludge treatment plant prior the incineration. WU sludge was discarded because its production needs and therefore its causality is unknown; this since the WU sludge generation is not done in CURRENTA WWTP. In Figure 8 is given a schematic representation of the system boundaries.

Background systems are considered: Upstream processes for the auxiliaries, as well as electricity and steam generation, are contemplated within the system Boundaries. Such background information was retrieved from LCI databases. Maintenance of buildings or process equipment was neglected.

A rough consideration for the construction phase is done to make an approximated comparison with the foreground system. This comparison is conducted just in terms of energy use for the tower and cascade biology tank construction considering energy in material, energy in delivery and energy on-site work. Even when this energy analysis is not used further in the LCIA it served as a basis to appreciate the energy use difference proportion between the operational and the construction stage. More detailed analysis in the construction is impossible because lack of data.

Section	Operation Stage
Pretreatment	Coarse Screen Lime Preparation Neutralization Primary Clarification Buffering
Tower Biology	Tower Biology Denitrification Flotation
Cascade Biology	Cascade biology Secondary Clarification
Waste Air Treatment	Incineration Washing
Sludge Treatment	Thickering Dewatering

Table 6. Process substages

The system under study is carefully organized by dividing the operation process (Describes in Chapter 2) into 5 sub sections or phases; this to identify afterwards which parts of the process are responsible for each environmental effect. Below in table 6 are shown these phases as well as the operation stages included in each one. The inventories comprise total amount of chemical auxiliaries, electrical energy, and thermal energy used CURRENTA wastewater treatment process per sub stage, as well as the water composition in terms of the already defined parameters. Minor auxiliaries like the ones utilized for analytical purposes are not considered. All data is from the 2010 operational period.

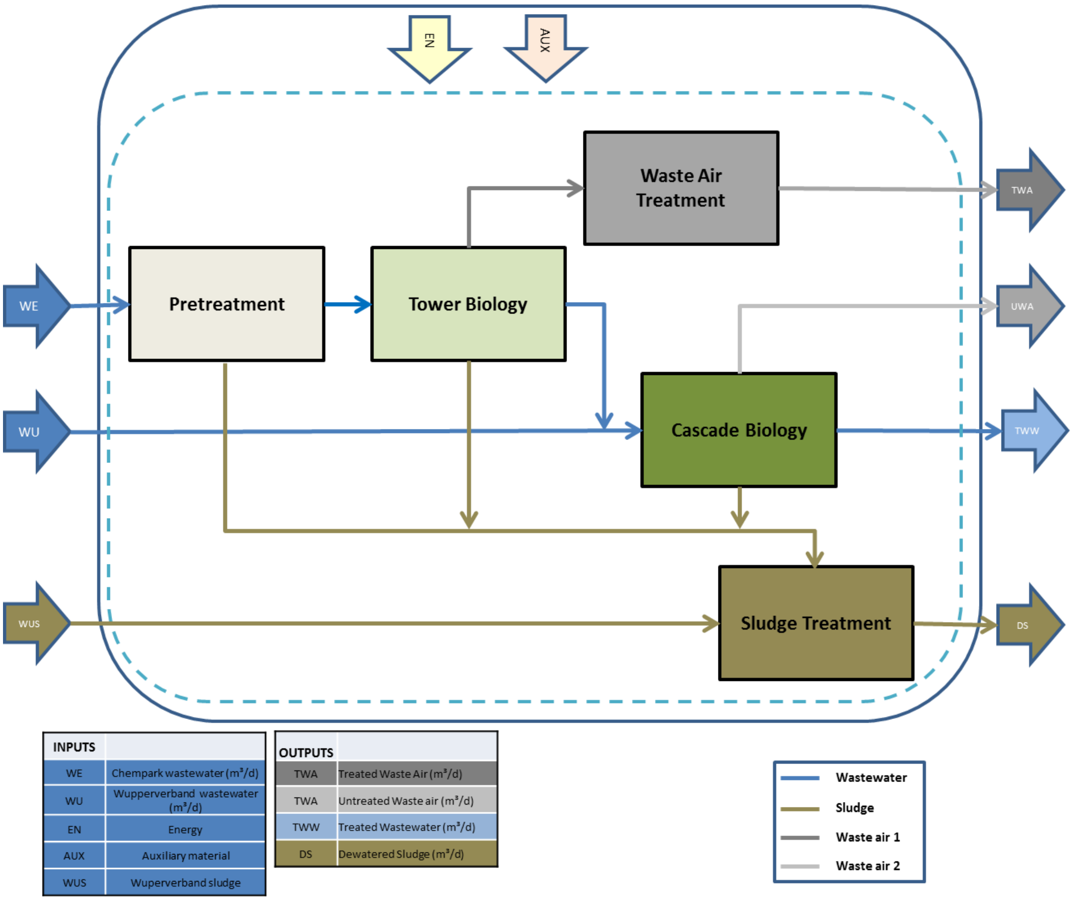

Figure 8. System boundaries

4.3. Functional Unit

The main purpose of Currenta WWTP is the removal of organic matter and nutrients from the wastewater and, consequently, the reduction of emissions when the treated effluent is discharged to river Rheine. Based in this, the functional unit was set in regards to the composition elements of the wastewater which want to be removed. There were chosen Hydraulics (Q), Total Organic Carbon (TOC), Total Nitrogen (N), Total Phosphorus (P) and Hydrogen (H^+) as main parameters to describe the wastewater elements. This because they describe the main functionality of the entire treatment process (TOC, N and P removal) and also are key wastewater pollutants regulated by German authorities for wastewater discharges (Deutsche Bundesregierung, 2004).

They were set 5 different functional units related to each other by the wastewater composition. They were then defined in terms of the 5 main composition parameters mentioned above (Q, TOC, N, P and H+) in order to manage changing "what if" scenarios depending in the variation of each one. Even when the 5 parameters were considered as functional unit, the referring base to make all calculations was 1 m^3 of treated wastewater in 2010.

4.4. Allocation procedures

Currenta wastewater treatment plant resembles a multi-input/output scheme (Figure 9); a number of different input elements with different properties are treated in the same system, and also several outputs are produced and leave the process. Under this scheme a problem of allocation arises to define the Life cycle Inventory since is needed a procedure to assign the input and output data only to those environmental burdens which each one generate (Azapagic & Clift, 1999).

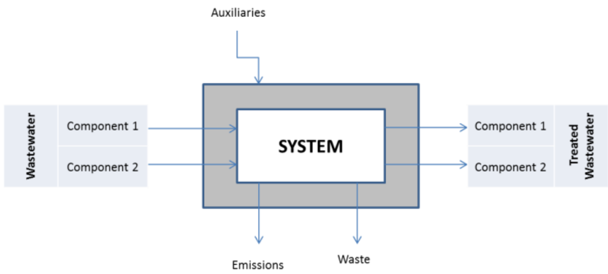

Figure 9. Multi input/output system (Azapagic & Clift, 1999).

Is then, that an multi-input/output allocation model is proposed in order to be able to define the Life Cycle Inventory (LCI) in Currenta Waste water treatment plant. To achieve this, the environmental impacts which are the consumption of ancillaries and energy carriers, the generation of sludge, and the emission of pollutants were partitioned to the wastewater composition by their specific cause. There were chosen Hydraulics (Q), Total Organic Carbon (TOC), Total Nitrogen (N), Total Phosphorus (P) and Hydrogen (H^+) as main parameters to describe the wastewater composition. In the following chapter is defined and explained the multi-input/output allocation model used in the present study.

4.5. Life Cycle Impact Assessment selected methodology

The methodology used for the impact assessment phase in the present study is the CML baseline. This methodology is part of the "Operational Guide to Life Cycle Assessment" of the Centre of Environmental Science, Leiden University, and fulfills the requirements of ISO 14042. It was chosen this evaluation system because it provides a problem oriented valuation method and its impact categories are generally used in most LCA studies (Guinée, et al., 2001).

This CML method comprises 14 impact categories to characterize a large number of substances, which are emitted into air, fresh water, sea water, agricultural soil and industrial soil. These impacts are listed in Table 7.

Impact category	Unit	Cause
Abiotic depletion	kg Sb eq	Natural resources, including energy resources, which are regarded as nonliving.
Global warming	kg CO_2 eq	Defined as the impact of human emissions on the radioactive forcing the atmosphere.
Acidification	kg SO_2 eq	Acidifying pollutants
Eutrophication	kg PO_4 eq	Covers all potential impacts of excessively high environmental levels of macronutrients
Freshwater aquatic ecotoxicity	kg p-DCB	Refers to the impacts of toxic substances on freshwater aquatic ecosystems
Freshwater sedimental ecotoxicity	kg p-DCB	Refers to impacts of toxic substances on the sediment of freshwater ecosystems
Human toxicity	kg p-DCB	Covers the impacts on human health of toxic substances preent in the environment.
Odour	m^3	Odorous substances above certain level
Terrestrial ecotoxicity	kg p-DCB	Refers to impacts of toxic substances on terrestrial ecosystems
Ozone Layer Depletion	kg CFC-11 eq	Is the formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants
Marinewater aquatic ecotoxicity	kg p-DCB	Refers to the impacts of toxic substances on freshwater aquatic ecosystems
Marinewater sedimental ecotoxicity	kg p-DCB	Refers to the impacts of toxic substances on the sediment of the sea water ecosystems.
Radiation	DALY	Covers the impacts arising from releases of radioactive substances as well as direct exposure to radiation.
Photochemical Oxidation	kg ethylene eq	Is the formaion of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants

Table 7. CML impact categories (Guinée, et al., 2001)

4.6. Data Requirement

The quality of data used in the life-cycle inventory is naturally reflected in the quality of the final result of LCA (Sonnemann, Castells, & Schuhmacher, 2004). In this frame, firstly in situ taken data on the processes involved were preferable. It was considered the average daily flow and composition (TOC, P and H+) of wastewater treated on an annual basis (2010) with typical Currenta WWTP operation. Mass and energy balances were employed where no direct measurements exist. Calculations based on the technical literature were used only if direct data could not be obtained.

CHAPTER 5. LIFE CYCLE INVENTORY

Life-cycle inventory is considered the step in Life Cycle Assessment in which all the environmental loads or environmental effects generated by a product or activity during its life-cycle are identified and evaluated (Sonnemann, Castells, & Schuhmacher, 2004). The life cycle model developed in a life cycle inventory analysis (LCI) should be an appropriate description of the relevant parts of the system (Ekvall & Weidema, 2004). In this chapter the LCI of the present case study is presented and explained considering foreground and back ground systems. Because Currenta wastewater treatment plant resembles a multi-input/output scheme allocation was unavoidable. For this reason it was necessary to design a multi-input/output allocation model to make the correct assignation of all inputs and outputs among the environmental loads generated. Within this context, in this section first the allocation model is introduced and then the results of the inventory are summarized. Due to confidentiality agreements with Bayer/Currenta company many of the data reported in this chapter is done with relative numbers calculated from the internal Currenta report "Life Cycle Inventory of CURRENTA-Leverkusen Wastewater Treatment Plant" (Almanza, 2012).

For the scenario with sludge digestion, the same inventory model described in this chapter was considered. Only the respective adjustments when required were done in the corresponding inflows (TOC and N load in TB), outflows (sludge volumes) and inputs consumptions (energy supply and auxiliaries).

5.1. Foreground system.

The foreground system is defined as the set of processes directly affected by the study, delivering the functional unit specified in Goal and Scope Definition (Azapagic & Clift, 1999). For the present study it makes reference to the wastewater treatment process that earlier in chapter 4 was divided in the sub stages Pretreatment, Tower Biology, Cascade Biology, Waste air treatment, and Sludge Treatment.

To carry out the inventory analysis for this foreground system, data was collected based on the process flow diagram of the Currenta WWT system according to the defined life-cycle boundaries defined in chapter 4. Qualitative and quantitative information concerning the process and its elementary flows for the year 2010 were established. The data sources used were mostly provided by the company. Mass and energy balances were employed where no direct measurements exist. Calculations based on the technical literature were used only if direct data could not be obtained. In Table 8 is given the relative consumption of ancillaries and energy carriers considered per sub stage. Quantities distribution of auxiliary materials used for certain sub stage processes or energy consumptions were estimated according Currenta expert's opinion.

Several authors have suggested multi-input/output allocation models. Particularly Kohler (2006) Recan (2005) and Dolka et al (2009) introduced a model to evaluate a wastewater treatment plant, where similarly than in the present case, the allocation model was presented in basis of the wastewater composition. To do this, they proposed the usage of consumption factors and transfer coefficients. The consumption factors to set the proportional relation between auxiliaries inputs including energy, and wastewater composition; and the transfer coefficients to establish the partitioning of the inflow wastewater elements among the outflow stream of the system which include the sludge, emission to air and discharge treated water to the receiving water body (Köhler, 2006). These two concepts are included in the present analysis making own new estimation considerations which are in the following section explained. By sub stage, it is clarified the allocation criteria and the calculation method of each of the factors considered in the present study.

Auxilary	Unit	Pretreatment	Tower Biology	Cascade Biology	Waste Air Treatment	Sludge treatment
Electrical energy	kwh/d	17%	55%	17%	6%	5%
Thermal Energy (steam)	kg/d	35%	25%	-	-	40%
Lime	kg/d	74%	6%	3%	-	17%
Fe salts	kg/d	-	-	35%	-	65%
Service water	L/d	25%	15%	15%	5%	40%
Polymer	kg/d	-	16%	60%	-	24%
Natural gas	L/d	5%	4%	-	85%	6%
Anti foamer	L/d	-	100%	-	-	-
3 bar air	L/d	-	100%	-	-	-
6 bar air	L/d	30%	20%	20%	-	30%
Instrument air	L/d	10%	20%	30%	10%	30%
Nitrogen gas	L/d	-	-	100%	-	-
Aluminate	kg/d	-	100%	-	-	-
Polyaluminum chloride	kg/d	-	-	100%	-	-
Acetone	kg/d	-	-	100%	-	-
Potable Water	L/d	25%	15%	15%	5%	40%
Amidosulfonic acid	kg/d	20%	35%	5%	-	40%
Activated Carbon	kg/d	-	-	100%	-	-
HCl (32 %)	kg/d	-	-	-	-	100%

Table 8. Auxiliary list (Adapted from Almanza, 2012)

Previously in Chapter 2, was presented in Table 2 the general daily flow and concentration input and output averages of Currenta WWTP. In that table, detailed information about the values of the parameters considered as functional unit of the system under study are proportionated. This include the already mentioned flow(Q), Total Organic Carbon (TOC), Total Nitrogen (N), Total Phosphorus (P) and Hydrogen (H+) of the entire system.

5.1.1. Pretreatment

This sub stage is comprised by the coarse screen, lime preparation, neutralization, primary clarification and the buffering systems. The main target here is the removal of coarse solids by screening, settle organic and inorganic solids by sedimentation, and make uniform operating parameters(flow, suspended solids and other pollutants, and temperature) over a given time frame (typically 24 hours) to reduce their downstream effects (WEF, 2008). In the "pretreatment" column of the Table 8 are listed all the auxiliaries inputs needed to achieve the above mentioned sub stage targets.

For the electricity requirements, it was used the data provided by the CURRENTA 2010 energy report (Kolisch, 2012) where is described in detail the energy consumption per equipment in the processes included in this sub stage. All the electricity consumptions regarding water transportation and mixing (pumps and stirrers) were assigned to the "Hydraulic" parameter. It can be appreciated that most of the electricity is needed in this concept (Table 9). Equipment electricity necessities destined to lime preparation were allocated to "Q", "P" and "H". This because the lime milk prepared with them has mainly two functions: The main one and given by the total quantity of H^+ ions is the neutralization of the stream; the second function is for phosphorous precipitation as $Ca_{10}(PO_4)_6(OH)_2$. According to the stoichiometric needs of each one was assigned the proportion 75 - 1% ("H^+"- "P") which pondered with the total electricity consumption in the pretreatment correspond to 16,21-0,18% respectively . This proportion later in the lime allocation part is fully clarified. The remainder 24% that is not included corresponds to excess lime milk quantity which its usage cannot be assigned stoichiometrically to H or P and was then allocated in Q. Electricity required for sludge pumps was distributed according to the primary sludge composition which equal approximately: 5 % Nitrogen (as particulate Nitrogen) (Doka, 2009); 1 % phosphorous (as Ca10(PO4)6(OH)2); 78% others (which is assigned to the "Q" parameter) and 17% TOC which correspond mainly of particulate organic matter (25-40% removed according to Metcalf & Eddy, 2003). Each of these values were pondered to the sludge pumps electricity consumption and proportionally assigned to the total overall. The final values are reported in Table 8. Detailed information of this available in the excel data base.

Parameter	%
Hydraulics	83,9%
H+	15,8%
P	0,18%
TOC	0,13%
N	0,04%

Table 9. Pretreatment electrical energy partitioning among the process parameters (Almanza, 2012).

Lime together with electricity represents here high significance consumption. As mentioned before this product has two functions; to neutralize the acidic influent from the Chempark and to chemically remove phosphorous by precipitating it. So, the lime usage was allocated in “P” and “H^+” parameters based in stoichiometrical relations. Additionally some amount was attributed to “Q” to quantify the lime which its usage cannot be clarified stoichiometrically.

It is known that where industrial wastes introduce acidic substances into the wastewater, these must be neutralized before any precipitation takes place (Metcalf & Eddy, 2003), that is why first was estimated the total amount of OH^- ions needed to neutralize the kg/d of H^+ present in the inflow according to the Equation 1.

$$Ca(OH)_2 \rightarrow Ca^{(2+)} + 2OH^-$$

Equation 1

The estimation result corresponds to 75% of the total amount of lime fed in the system as CaO (Almanza, 2012).

As the pH value increases excess calcium ion react with the phosphate present, to precipitate hydroxylapatite (Equation 2). Contemplating that the reported phosphorus removed is phosphate, and considering the equation 2, the quantity of lime milk consumed in pretreatment sub stage is approximately 1% of the total.

$$10Ca^{(+2)} + 6PO_4 + 2OH^- \rightarrow Ca_{10}(PO_4)_6(OH)_2$$

Equation 2

The remainder 24% concerning pretreatment lime consumption that is not included in H or P corresponds to lime milk quantity because inert matter present or excess fed for buffering purposes. As it cannot be justified stoichiometrically to H or P, it was attributed to Q. Note that the same allocation distribution (75-1-24%) proportion was also used above to allocate the lime preparation equipment electricity necessities.

Amid sulfonic acid which is used to clean lime milk lines was allocated with the same criteria than lime because its usage is function of the lime consumed.

Thermal energy (steam), service water, natural gas, 6 bar air, potable water and instrumental air were contemplated as general consumption ancillaries. This because they do not have a specific function regarding the main parameters (they do not depend on them), but are used somehow in the process (See Table 10 below). It was considered to attribute them to wastewater volume treated, which means that 100% of their consumption was allocated to the average flow.

In Table 11 finally is summarized in percentage the distribution of each auxiliary in the pretreatment sub stage according to the wastewater composition.

Auxiliary	Function
Thermal Energy (steam)	Heating purposes
Service Water	Miscellaneous: Cleaning, cooling, sealing.
Natural Gas	Heating purposes
6 bar air	Miscellaneous: Lime silos operation, cleaning.
Potable Water	Miscellaneous: Bathrooms, sinks
Instrumental air	Instrumentation

Table 10. General consumption ancillaries function (Almanza, 2012).

Auxiliary	Q	TOC	N_T	P_T	H^+
Electrical energy	79,7%	0,1%	0,04%	3,9%	16,2%
Thermal Energy	100,0%				
Lime				25,0%	75,0%
Amidosulfonic acid				25,0%	75,0%
Natural Gas	100,0%				
Service water	100,0%				
6 bar air	100,0%				
Potable Water	100,0%				
Instrumental Air	100,0%				

Table 11. Allocation proportion in Pretreatment sub stage (Almanza, 2012).

5.1.2. Tower and Cascade Biology

5.1.2.1. Electric Energy

The allocation criteria regarding the energy assignation in the Tower and Cascade biology was done in function of the hydraulics, TOC, N and P. For the hydraulic electricity requirements, it was used the data provided by the CURRENTA 2010 energy report where is described in detail the energy consumption per equipment in the whole plant. For TOC and N electricity is consumed for providing oxygen via aeration to the aerobic elements in the biological system, and also to transport the sludge produced by them. So it was necessary a mass balance to determine the amount of oxygen that must be supplied to satisfy the energy and nutrient needs of the microorganisms, as well as their sludge production. Moreover it is also produced sludge consequence of the precipitation reaction of phosphorous chemical removal, which also was considered.

5.1.2.1.1. Aeration

As described before, all biological reactions need a final electron acceptor to complete the oxidation-reduction process. In the Currenta biological system the electron acceptors are oxygen (in organic matter and ammonium oxidation), and nitrate (in anoxic denitrification). Therefore, oxygen must be supplied to satisfy the needs of the microorganisms; in this case, this is achieved by aeration. Aeration serves a dual purpose: supply of the oxygen needed for bacterial metabolism and contaminant oxidation, and mixing of reactor contents in order to keep the mixed liquor suspended solids in suspension and well distributed within the reactor. Oxygen is delivered to the aeration liquid through diffused aeration, in which compressed gas is passed through submerged diffusers and rises through the liquid as bubbles. (Rittman & McCarty, 2001)

As explained in the process description, the system has two biological systems, Tower and Cascade biology, which work with different wastewater characteristics and operational conditions. The following describes the allocations decisions and the calculation procedures used in each one (CURRENTA, 2009).

The tower biology has a special aeration system called BAYER Slot Injector where the kinetic energy of the propelling water drags air into the injector, brakes the gas into small bubbles, and pushes the fine bubble water/air dispersion into the activation tank, making the oxygen transfer highly efficient (Bayer, 2009). Electricity consumption is mainly due to the production of the 3 bar compressed air and propelling water used in the injector to generate the small bubbles. These bubbles provide the oxygen needed for the nitrification and the carbon degradation (NH_4^+ oxidation and TOC degradation by microorganisms).

In the cascade biology, the electricity consumption is mainly due to the 4 compressors of the air blowers of the activated sludge treatment. Air supplies the oxygen needed for the biochemical reactions that take place in the cascade (CURRENTA, 2009).

Electricity can thus be allocated to NH_4^+, which is nitrified, and de TOC, which is oxidized. The denitrification stage, in the tower biology, precedes the nitrification and carbon removal stages. Thus a part of the TOC, which otherwise had to be oxidized in the tower biology process gets oxidized in the denitrification tank under anoxic conditions with nitrate as electron acceptor. In the cascade, the nitrification-denitrification systems alternate along the reactor, so is possible to get the same effect with the TOC in the denitrification stages.

So, the energy assignation in the biological system regarding to aeration was done as follows:

1) Calculation of Oxygen demand in Tower and Cascade biology according to the load, stoichiometry and biochemical parameters.
2) Definition of proportional factors, where the percentages of oxygen for carbon removal and nitrification are shown. It is considered also the amount of oxygen saved because oxidation with nitrate in denitrification.

In the next paragraphs is described each of the above points mentioned.

For the calculation of the oxygen demand, it was used the German design guideline A 131 "Design of single stage activated sludge plants". In this guideline, the oxygen uptake is calculated separately for carbon removal and for nitrogen removal, what allows estimating the proportional use of the oxygen in the biological system. The guideline was applicable to both CURRENTA biological systems: Tower and Cascade biology (ATV, 2000).

For the carbon elimination, the following approach to the coefficient of Hartwig was used:

$$OV_{d,C} = B_{d,BOD} \cdot (0{,}56 + \frac{0{,}15 \cdot \theta_x \cdot F_T}{1 + 0{,}17 \cdot \theta_x \cdot F_T}) [kgO_2/d]$$

Equation 3

$$F_T = 1{,}072^{(T-15)}$$

Equation 4

Where,

$OV_{d,C}$ = Daily consumption of oxygen for carbon elimination (kg O_2/d)

F_T= Temperature factor for endogenous respiration

$B_{d,BOD}$= Daily BOD load

θ_x= Solid retention time (d)

In this coefficient, typical parameters describing growth and substrate utilization for heterotrophs are used, where biomass yield and endogenous rate are included in the factors considered (ATV, 2000). The 0.56 represents the true biomass yield assuming a cellular composition of $C_5H_7O_2N$ and a portion of electron transferred into microbial cell for synthesis equal to 0.8. So we have:

$$Y = 0.8 \frac{\text{e-eq. cells}}{\text{e-eq. donor}} \cdot \frac{113\ g\ VSS}{20\ \text{e-eq. cells}} \cdot \frac{1\ \text{e-eq. donor}}{8\ \text{g BOD}} = 0.56 \frac{\text{g VSS}}{\text{g BOD}}$$

Equation 5

In which 113g is the empirical formula weight of cells, 20 e- eq/mol cells is the number of electron equivalents in an empirical mole of cells, and the donor mass is expressed as BOD.

The 0.15 and 0.17 values represent the endogenous decay. The endogenous decay rate (b) depends on species type and temperature. For this case, in which there are aerobic heterotrophs, b has values of 0.1 to 0.3/d at 20°C, while the slower-growing species have b < 0.05/d. The temperature effect on b can be expressed by a F_T. Endogenous decay coefficients normally encompass several loss phenomena, including lysis, predation, excretion of soluble materials, and death (Rittman & McCarty, 2001).

For nitrification, the oxygen consumption of 4.3 kg O_2 per kg of oxidized nitrogen is assumed taking into account the metabolism of the nitrifiers. This can be demonstrated in the reaction below. This equation is an overall, balanced reaction for the complete oxidation of NH_4^+ to NO_3^--N by nitrifiers (Henze, Horremoës, La Cour Jansen, & Arvin, 2002):

$$NH_4^+ + 1{,}86O_2 + 1{,}98HCO_3 \rightarrow 0{,}020C_5H_7O_2N + 0{,}98\ NO_3^- + 1{,}04H_2O + 1{,}88H_2CO_3$$

Equation 6

1,86 mole(32g/mole) O_2/0.98mole(14g/mole)-NO_3-N = **4,3 g- O_2/g- NH_4^+-N oxidized of the nitrifiers.**

This stoichiometric equation illustrates the 4,3 g- O_2/g- NH_4^+-N oxidized equivalent calculation that is used below in the A 131 guideline formula.

In the case of denitrification, anoxic conditions are established for denitrification by facultative bacteria, which would use oxygen preferentially for energy production if available. In both tower and cascade cases, due the anoxic conditions and configuration of the process, part of the nitrate generated in the nitrification stage is used as electron acceptor. It can be considered then the following reaction:

$$CH_2O + 0{,}8NO_3^- + 0{,}8H^+ \rightarrow 0{,}4N_2 + 1{,}75\ H_2O + 1{,}25CO_2$$

Equation 7

$$CH_2O + O_2^{\ +} \rightarrow H_2O + CO_2$$

Equation 8

1mole(32g/mole) O_2/0.8mole(14g/mole)-NO_3-N = **2.86 g- O_2/g- NO_3-N**

What means that each gram on nitrate consumed in respiration saves 2.9 gram of oxygen (Henze, Horremoës, La Cour Jansen, & Arvin, 2002).

Having explained the above equivalents, the daily oxygen uptake for nitrification $OV_{d,N}$ (kg/d) and the daily oxygen equivalent from denitrification $OV_{d,D}$ (kg/d) become:

$$OV_{d,N} = Qd \cdot 4{,}3 \cdot (S_{NO3,D} - S_{NO3in} + S_{NO3out}) [kgO_2/d]$$

Equation 9

$$OV_{d,D} = Qd \cdot 2{,}9 \cdot (S_{NO3,D}/1000) [kgO_2/d]$$

Equation 10

Where,

$OV_{d,N}$= Daily consumption of oxygen for nitrification (kg O_2/d)

$OV_{d,D}$= Daily saved consumption of O_2, which is covered by denitrification (kg O_2/d)

$S_{NO3,D}$= Concentration of denitrified nitrate to nitrogen (mg/l)

$S_{NO3,in}$= Inlet Concentration of nitrate (mg/l)

$S_{NO3,out}$= Outlet Concentration of nitrate (mg/l)

Q_d = Daily wastewater flow during dry weather (m^3/d)

$S_{NO3,D}$, $S_{NO3,in}$, and $S_{NO3,out}$, as well as Q_d were provided by CURRENTA during data compilation stage.

Finally, with the daily consumption of oxygen for carbon elimination and nitrification, and the daily consumption of O_2 which is covered by denitrification, it is possible to estimate the total quantity of oxygen required in the biological systems:

$$OV1 = OV_{d,C} + OV_{d,N} - OV_{d,D} [kgO_2/d]$$

Equation 11

In Table 12 are then reported the results for the Tower and Cascade biology using the guideline above described. Because the operational data is defined in terms of COD and the design guideline is in BOD, a ratio value BOD/COD of 0.6 was considered to make the conversion. This ratio is the typical for municipal wastewater, which is basis for the guideline (ATV, 2000). Note that the values reported are relative. The intention is give the proportion variation depending on the system and the biological use (carbon removal, nitrification or denitrification).

	Tower	Cascade WU+WE
Q_d (m^3/d)	1,01	2,29
$OV_{d,C}$ (kg O_2/d)	**0,96**	**0,425**
$OV_{d,N}$ (kg O_2/d)	**0,17**	**0,126**
$OV_{d,D}$ (kg O_2/d)	**-0,14**	**-0,12**
Total (kg O2/d)	**1,00**	**0,43**

Table 12. Oxygen requirments estimation. Relative values adapted from Almanza, 2012

Next, the oxygen transfer capacity of the aeration facility has to be taken into account. It must be considered that an important practical limitation on the BOD loading to a biological system is related to the amount of oxygen that can be transferred to the reactor economically and without destroying the sludge floc (Ramalho, 1977). Whatever the aeration technology used, the rate of oxygen transfer between phases is governed by mass transfer from the bulk gas to the gas-liquid interface, and then from the gas-liquid interface into the liquid. For sparingly soluble gases such as oxygen, the transfer to the gas-liquid interface is fast compared with that from the interface into the liquid; thus, the liquid-side transfer is rate limiting (Rittman & McCarty, 2001).

To calculate the total required oxygen was considered the function below (ATV, 2000) where the total amount of oxygen needed in the biological system is related with the liquid phase oxygen concentration in equilibrium with bulk gas phase (C_S); the liquid phase bulk oxygen concentration (C_x), and the factor α, which expresses the difference between K_La of wastewater and clean water. This mentioned K_La value depends very much on the aeration system used, the power input to the system, the shape and size of the aeration basin, temperature, and the characteristics of the wastewater (Ramalho, 1977).

$$\propto \mathrm{OC} = \frac{C_S}{C_S - C_X} \cdot \mathrm{OV} \ \ [kgO_2/d]$$

Equation 12

Where,

OC= Total oxygen needed in the aeration

C_S= liquid phase oxygen concentration in equilibrium with bulk gas phase (mg/l),

C_x= liquid phase bulk oxygen concentration (mg/l).

α = Correction factor

$$\propto = \frac{K_L a\ (wastewater)}{K_L a (clean\ water)}$$

Equation 13

Where,

K_La= volumetric mass transfer rate coefficient (d^{-1}).

The value for α is reported to vary from 0.35 to 0.8 for diffused aeration. For our system, according to operational experience, the values used in the Tower and Cascade biology were of 0.9 and 0.7

respectively. In Table 13 are shown the values considered, as well as the total calculated amount of oxygen relatively needed to be supplied to each system.

	Tower	Cascade
Total (kg O2/d)	1,00	0,43
C_s (mg/l)	7,56	9,34
C_x (mg/l)	2,00	2,00
α	0,90	0,70
OV (kg O2/d)	**1,51**	**0,78**

Table 13. Total oxygen requirement considering transfer rate. Relative values adapted from Almanza, 2012

The process deals with carbon and nitrogen removal that consist in biochemical reactions that are due the biological activity of heterotrophic and autotrophic microorganisms occurring inside the reactors. Because the oxygen uptake was calculated separately for carbon removal and for nitrogen removal, was also possible to know exactly how much oxygen is used for carbon removal, for ammonium removal, and how much is saved by reason of the denitrification. This later on is the basis for our allocation criteria. In the graphic below is shown the usage according the biochemical process in the Tower and Cascade Biology.

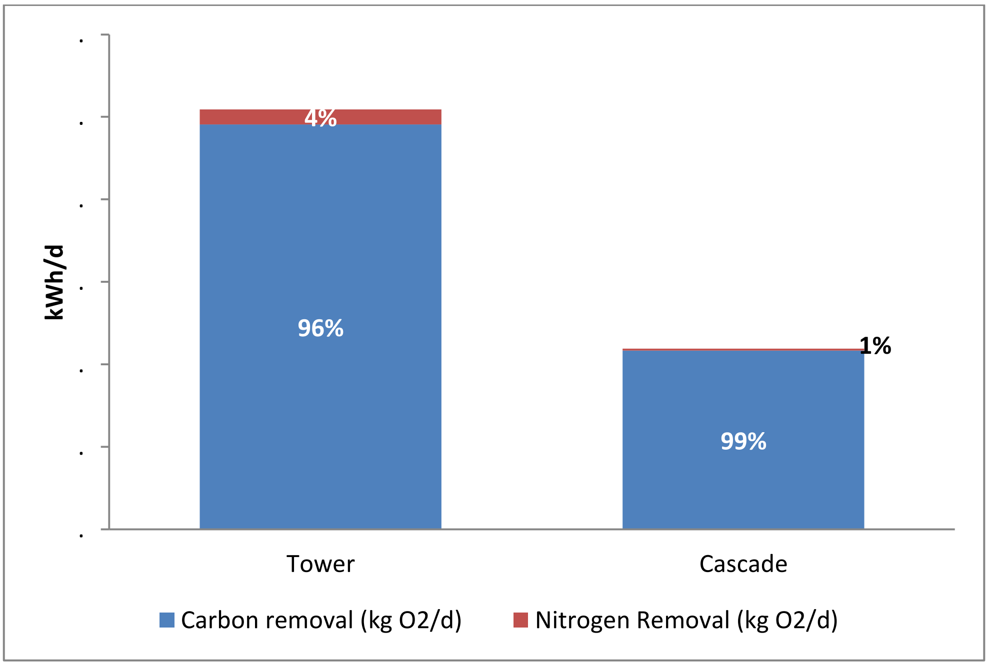

Figure 10. Oxygen use according the biological process (Almanza, 2012)

A special note has to be made regarding these distributions: It was assumed that the daily saved consumption of O_2 which is covered by denitrification is totally given by the inlet Nitrogen concentration, i.e., if higher nitrogen concentration is fed more nitrate is going to be produced and therefore more oxygen in the aerobic reactor saved. From this point of view, the evaded oxygen in denitrification was deducted to nitrification so later would be able to conform a single concept of nitrogen removal oxygen allocable to the parameter N. Moreover, nitrate present in the inlet of the system also contributes for oxygen saving in nitrogen removal.

It can be seen in the Figure 10 that in the Tower biology, 4% of the oxygen up taken is used for nitrogen removal, while the remaining 96% is for carbon compounds elimination. In the cascade this relation is 99-1% respectively. This proportion indicates that, because daily saved oxygen in denitrification, both systems show to be almost autonomous in their nitrogen removal oxygen consumption. The percentages values presented here are used as proportional factors to allocate the energy consumption to the main parameter values of Flow, TOC and Total Nitrogen, of the defined model system.

5.1.2.1.2. Sludge Production

The 3 biological mechanisms already explained in the previous section (Carbonaceous organic matter oxidation, nitrification and denitrification) involve in their respective conversion process the production of additional biomass (sludge). Additionally to the biomass, it is also produced sludge consequence of the precipitation reaction of phosphorous chemical removal. This total sludge represents in both tower and cascade biology supplementary mass that generates additional electrical energy consumption to achieve their manipulation (sludge pumps and scrappers). According to this context, it is necessary to differentiate the source of the sludge production to later on be able to allocate it to its causal parameter. For this reason, it was estimated the amount of sludge originated from carbon removal, nitrification, denitrification and phosphorous precipitation and then and there assigned each proportionally to TOC, N and P.

For carbon removal microorganisms (heterotrophic) sludge production, it was used the following equation proposed by Rittman (Rittman & McCarty, 2001) using typical kinetics parameters:

$$Sludge\ Production = Q(S^0 - S)Y\frac{1 + (1 - f_d)b\theta_x}{1 + b\theta_x}$$

Equation 14

Where,

Q = Daily wastewater flow (m^3/d)

S^0= Organic carbon concentration in the inflow (mgDBO/l)

S = Organic carbon concentration in the outflow (mgDBO/l)

f_d = active biomass fraction that is biodegradable

b = Endogenous decay rate (d^{-1})

Y = Biomass synthesis yield (mgVSSa/mgBOD)

θ_x= Solid retention time (days)

Q, S^0, and S were given in the reported data provided by Currenta. For Y, f_d and b typical values of 0.6, 0.8 and 0.15 respectively were taken (Rittman & McCarty, 2001).

The nitrification sludge, which have a low net formation of biomass, was estimated with the same equation than the heterotrophic but with the respective typical kinetics values Y, f_d and b of 0.4, 0,8 and 0.005 respectively. In this case S^0, and S correspond to TKN and NH_4 concentration in mg/l.

For denitrifiers was considered the following equation below (Rittman & McCarty, 2001):

$$DSP = \frac{\left((Q \cdot TKN^0) - \frac{NSP}{Y_{n(nit)}} \right) - (0{,}124 \cdot HSP)}{0{,}124}$$

Equation 15

Where,

Q = Daily wastewater flow (m^3/d)

DSP= Denitrifier sludge production (kg/d)

TKN^0= TKN concentration in the inlet (mg/l)

NSP = Nitrifiers sludge production (kg/d)

HSP= Heterotrophics sludge production (kg/d)

$Y_{n(nit)}$= Nitrifier biomass synthesis yield (mgVSSa/mgBOD)

0,124= Typical nitrogen content in biomass (mgN/mgVSS)

To the utilization of this formula was assumed that NO_3-N is completely denitrified in the anoxic reactor or $(NO_3)^1$ = 0. Likewise, Organic matter and TKN are fully oxidized in the aerobic reactor, making BOD^1 = TKN^2 = 0, while the maximum amount of NO_3-N is generated in the aerobic reactor, $(NO_3)^2$. A $Y_{n(nit)}$ of 0,24 and 0,33 for the tower and cascade biology was considered respectively.

Table 14 shows the resulting sludge production in the tower and cascade biology according to the estimation method above described.

	Tower	Cascade
Q_d (m^3/d)	1,01	2,29
HSP (kg/d)	0,19	0,08
NSP (kg/d)	0,01	0,02
DSP (kg/d)	0,02	0,01
TOTAL (kg/d)	0,22	0,12

Table 14. Sludge production in biological systems (Almanza, 2012).

Finally, to estimate the sludge from chemical phosphorous removal, it was contemplated the precipitation stoichiometry of the phosphate reaction with the respective auxiliary used: Sodium aluminate ($Na_2Al_2O_4$) in the tower and iron chloride in the cascade ($FeCl_2$). Each reaction is illustrated below.

$$3FeCl_2 + 2PO_4 \rightarrow Fe_3(PO_4)_2$$

Equation 16

$$Na_2Al_2O_4 + 2PO_4 + 6H \rightarrow 2AlPO_4 + 2NaOH + 2H_2O$$

Equation 17

Here, PO_4 was taken for the reported data provided by Currenta and produced $Fe_3(PO_4)_2$ and $AlPO_4$ quantities were considered as generated sludge.

In Table 15 are summarized the proportionally the sludge production in the Tower and Cascade biology. HSP is assigned to TOC; NSP and DSP are both accredited to N; and $Fe_3(PO_4)_2$ and $AlPO_4$ are attributed to P.

	Tower	Cascade
TOC	82%	62%
N_T	13%	26%
P_T	5%	12%

Table 15. Sludge proportions according to wastewater parameters (Almanza, 2012).

So, for electrical energy consumption, all the equipment listed in Currenta energy report (Kolisch, 2012) that has a related sludge task, was divided according to these percentages. In the next section this information is complied with the aeration proportional factors to get the overall allocation for energy consumption in the Tower and Cascade biology.

5.1.2.1.3. Allocation of energy consumption

The CURRENTA 2010 energy report describes the total energy consumption per stage and equipment in the whole wastewater treatment process (Kolisch, 2012). Depending on the functionality of each equipment, the electric energy utilization was analyzed and assigned either to the flow or the wastewater pollutants removal (defined by TOC, N and P in the selected parameters).

In the tower biology, the major proportion of electricity is consumed for supplying oxygen for the biological processes (60%). This consumption is accredited, to the 3 bar compressed air and propelling water used in the injector to generate aeration to the system. 12 % conform the electricity utilization for pumping and stirring (Hydraulics); and around 1% is for sludge related activities (recirculation and extraction). Furthermore, 27% of the electricity which apparently would correspond to Hydraulics was taken separately as N recirculation. This concept belongs to Tower Biology recirculated wastewater volume. This recirculation is done to reach an adequate nitrate concentration that allows denitritrification and has approximately a ratio of 3.2. In the Figure 11 below is shown the proportion of each concept.

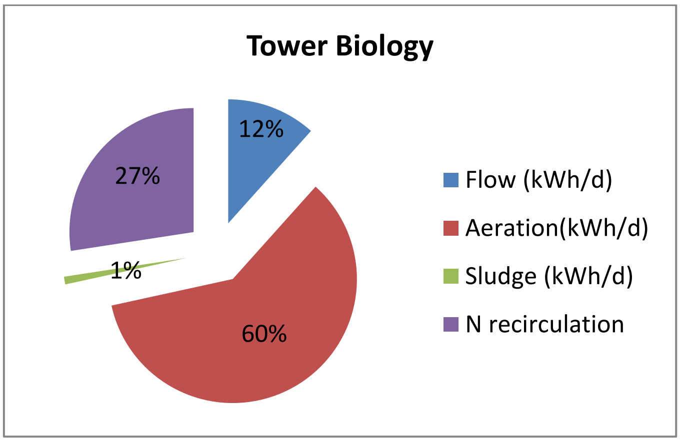

Figure 11. Electricity proportion consumption Tower Biology (Almanza, 2012).

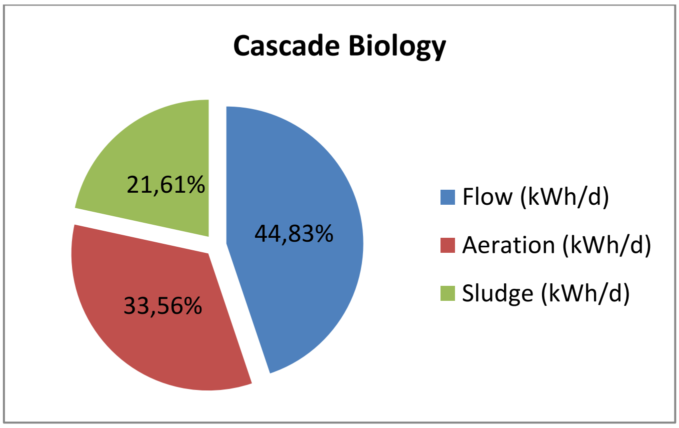

Figure 12. Electricity proportion consumption Cascade Biology (Almanza, 2012).

In the cascade biology the most electrical energy consuming activities are those related with hydraulics (44,83%), this high percentage is mainly because is not possible to carry the quantity of wastewater from the cascade biology to the Dortmund tanks by gravity, so it is necessary to have a pumping station which increase the electricity consumption. After hydraulics, the aeration is the most power demanding process by cause of the aeration system (4 turbo compressors) which accounts about 33.56% of total energy consumption. Sludge related activities, recirculation pumps and scrappers, signify 21.61%. In Figure 12 are given these proportions.

Once defined the total consumption proportions in both systems (tower and cascade) it was possible to make the distribution by causality to Hydraulics, TOC, N and P. Aeration was split in TOC and N according proportional factors in Figure 10 (sub section 5.1.2.1.2) . Sludge was divided in TOC, N and P using the relative percentages in Table 14. N recirculation referred in the Tower Biology was allocated totally to N because its ratio depends on how much nitrogen needs to be eliminated. In the graphic below is shown finally the distribution in terms of the process parameters.

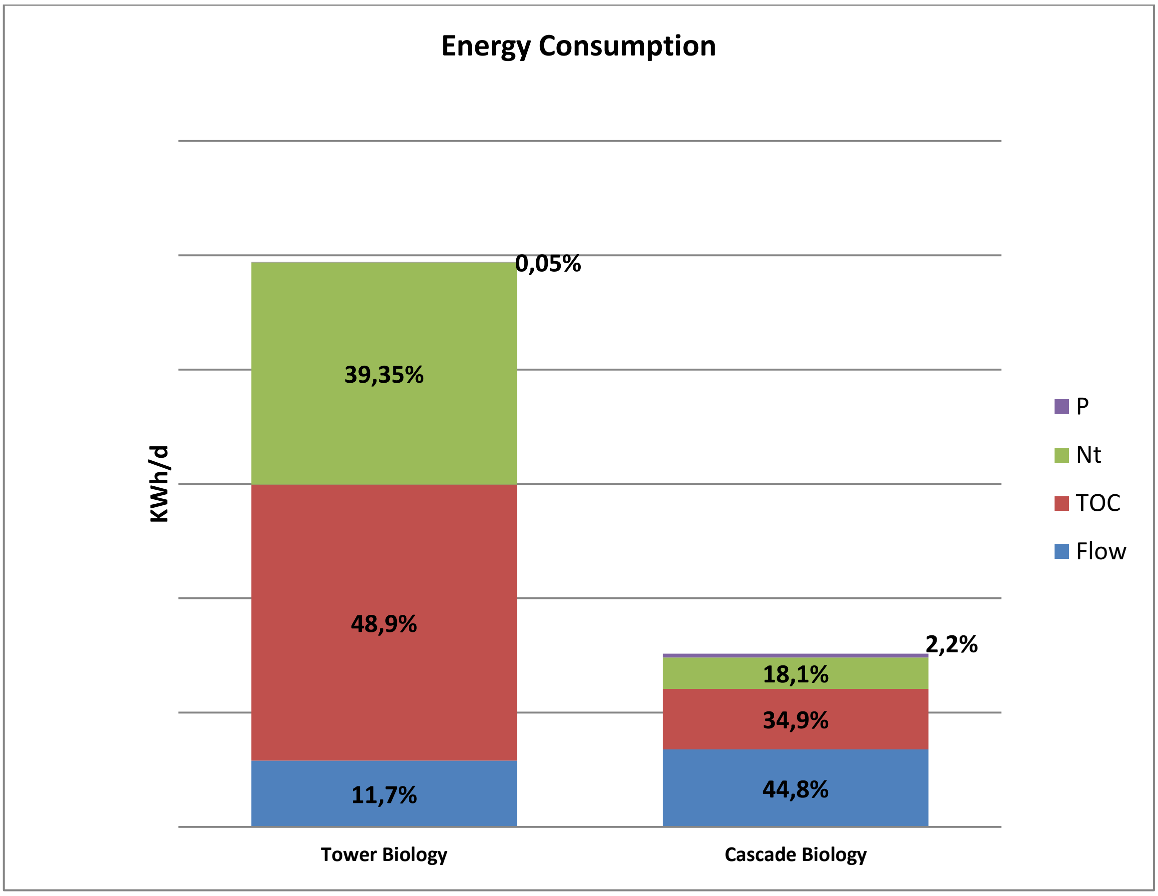

Figure 13. Electricity consumption distribution (Almanza, 2012).

According to these distribution percentages, it can be set the allocation for the total energy consumption in the tower and cascade biology.

5.1.2.2. Other Auxiliaries

Much foam is produced on the surface both in the tower and in the cascade biology. This is a very common problem in secondary biological systems that are attended in CURRENTA WWTP with antifoam in the tower and with PAC in the cascade. The causative microorganisms foaming usually belong to the genuses Nocardia (DeWitt & Wagoner, 2011), a nitrifier bacteria. For this reason the consumption of auxiliaries designed to foaming control were allocated totally to “N” parameter.

Lime is used in the tower and cascade biology to keep the pH in an adequate level. This is necessary because nitrification produces in its reaction strong-acid equivalents per mole of NH_4 removed (Equation 6) (Rittman & McCarty, 2001), i.e., ammonium oxidation causes acid production that is neutralized with $Ca(OH)_2$. Under this judgment, lime used in both tower and cascade biology was attributed totally to “N” parameter. Amid sulfonic acid which is used to clean lime milk lines was allocated with the same criteria than lime because its usage is function of the lime consumed, i.e., assigned to N.

As it was shown in previous section (sub section 5.1.2.1.2) in the chemical reactions to explain the sludge production, iron and aluminum salts are used to remove phosphorus via precipitation: Sodium aluminate ($Na_2Al_2O_4$) in the tower and iron chloride in the cascade ($FeCl_2$).The addition of this auxiliaries are exclusively for this phosphorous elimination, thus allocated to P.

Thermal energy (steam), polymer, service water, natural gas, 6 bar air, potable water and instrumental air were contemplated as general consumption ancillaries by lack of usage causality information. It was considered to attribute them to wastewater volume treated, which means that 100% of their consumption was allocated to the average flow. Thermal energy and natural gas are not used in the cascade biology. Polymer is used in flotation (TB) is to enhance attachment of sludge flakes to air bubbles and in Secondary clarification (CB) to improve sedimentation.

In Table 16 finally is summarized in percentage the distribution of each auxiliary in the cascade and tower biology according to the wastewater composition.

Auxiliary	Q		TOC		N_T		P_T		H^+	
	TB	CB	TB	CB	TB	CB	TB	CB	TB	CB
Thermal Energy	100%	-								
Lime					100%					
Amidosulfonic acid					100%					
Natural Gas	100%	-								
Service water	100%	100%								
6 bar air	100%	100%								
Potable Water	100%	100%								
Instrumental Air	100%	100%								
Polymer	100%	100%								
Sodium aluminate							100%			
Iron chloride								100%		
Anti foam					100%	-				
PAC					-	100%				

Table 16. Auxiliary allocation (Almanza, 2012).

5.1.3. Waste Air Treatment

In this part of the system, the extracted air from the neutralization stage and the respiratory air from the buffering tank are deodorized thermally together with the exhaust air from the tower biology. The foregoing with the aim of removing remainder organic matter in the emissions. In the "Waste air treatment" column of the Table 8 are listed all the auxiliaries inputs needed to achieve this removal.

A special particularity can be found in this sub stage: Even when the allocation is done to the main wastewater composition parameters, the inflow and outflow here consist of gases and not wastewater. So, before assigning ancillaries to the wastewater composition it was necessary to define the specific cause of this stage regarding the wastewater based in response to the change. To make this causality it was considered that organic load present in the stream, which its removal is the objective of this treatment, is mainly consequence of biological activity in the tower biology to eliminate TOC and N. This means that the higher TOC and N concentrations are in the Tower biology inlet, the greater will be the air supply there, what at the end will signify a more elevated organic load to be incinerated. This as final consequence will increase the sub stage ancillaries' consumption. Based on these assumptions, TOC and N were recognized as the parameters to which the auxiliaries in waste air treatment are allocated. To set the proportion of each one, it was taken into consideration the TOC and N oxygen requirement distribution for the tower biology estimated in the prior section (96% TOC removal and 4% N removal). The same factors were contemplated to all auxiliaries here because the process was considered as a whole with a shared specific function of cleaning exhaust air through incineration. Table 17 shows the resulting allocation distribution recognized in this sub stage.

Auxiliary	Q	TOC	N_T	P_T	H^+
Electrical energy		96%	4%		
Natural Gas		96%	4%		
Service water		96%	4%		
6 bar air		96%	4%		
Potable Water		96%	4%		
Instrumental Air		96%	4%		

Table 17. Allocation proportion in Waste air treatment sub stage (Almanza, 2012).

5.1.4. Sludge Treatment

In sludge treatment sub stage solids (sludge) from the wastewater treatment plant must be thickened (concentrated) and dewatered to comply with environmental regulations and minimize the volume to be disposed (WEF, 2008). This step encompass then the operation of one thickener (2 available) that increase the solids content by removing a portion of the liquid fraction; and 9 press filters that physically reduce moisture content on biosolids. Between these two actions, a conditioning with lime, iron salts and polymer takes place to improve dewatering properties.

In brief, it can be said that the main function of the sludge treatment process is to increase the total solids content of the solids produced in the wastewater treatment plant, and therefore all auxiliaries required (Table 19) here are added to fulfill this objective.

It can be noted that, as in the waste air treatment, the inflow and outflow do not consist in wastewater but sludge. In this case, the allocation to the wastewater composition was done based on the sludge production causality, i.e., if it is because organic matter degradation, nitrogen elimination or phosphorous removal. This was taken for the already estimated sludge production proportion explained for the biological systems (sub section 5.1.2.1.2 for tower and cascade biology) plus a contemplation of the primary sludge from the pretreatment sludge that was not considered earlier because it is not biologically produced (same distribution mentioned in section 5.1.1). WU sludge was discarded because its production needs and therefore its causality is unknown; this since the WU sludge generation is not done in CURRENTA WWTP.

The input data about the auxiliaries needed in the sludge treatment plant were referred according to the total sludge, including the WU sludge. To discard the WU sludge as mentioned it was necessary to deduct its auxiliary usage proportionally to its percentage in the total (16%). In this manner only WE sludge minus Wu sludge was examined with their corresponding auxiliary consumption ratio.

The estimated sludge production proportion remains as it is described in the Table 18 below. The same factors were contemplated to all auxiliaries here because the process was considered as a whole with a shared specific function of increase total solid content of sludge.

Parameter	Primary %	Secondary %
Q	77%	-
C	17%	74%
N	5%	18%
P	1%	8%
Total	100%	100%

Table 18. Allocation proportion in sludge treatment sub stage (Almanza, 2012).

Auxiliary	Q	TOC	N_T	P_T	H^+
Electrical energy	43%	42%	11%	4%	
Thermal Energy	43%	42%	11%	4%	
Lime	43%	42%	11%	4%	
Fe salts	43%	42%	11%	4%	
Service water	43%	42%	11%	4%	
Polymer	43%	42%	11%	4%	
6 bar air	43%	42%	11%	4%	
Instrumental Air	43%	42%	11%	4%	
Potable Water	43%	42%	11%	4%	
Amidosulfonic acid	43%	42%	11%	4%	
Natural Gas	43%	42%	11%	4%	
HCl (32 %)	43%	42%	11%	4%	

Table 19. Allocation proportion in sludge treatment sub stage (Almanza, 2012).

With the sludge digestion inclusion the sludge treatment sub stage is modified. To calculate the inventory analysis of this sub stage for this new scenario the same model described above was used taking into consideration the following adjustments:

-Biological (tower and cascade biology) and Wupperverband sludge volume is reduced in the anaerobic digestion phase by 60%. Primary sludge from pretreatment is not digested; therefore its volume remains the same.

-Because additional processes that requires the inclusion of the sludge digestion, an increment in the electrical energy consumption is contemplated. Considering this is expected to duplicate the actual electrical energy consumption in the sludge treatment stage.

- Methane production. Considerable amount of methane, which represents revenue to the process, is produced. This methane production was deducted from natural gas supply volume to quantify the profit in the contrasting scenario.

-Auxiliaries adjustment. Is expected a decrement of 30% in most of the auxiliaries consumption. Nonetheless, a considerable increment is predicted in HCl and steam: 4300% and 300% respectively. Also an additional auxiliary, which is NaOH, is included.

- TOC and N concentrations increment 1% and 14% respectively in the inlet of tower biology because the recirculation of highly concentrated supernatant from digested sludge thickening and dewatering.

5.1.5. Resulting Model

The resulting model of multi-input/output allocation include consumption factors and transfer coefficients, which can be used for calculating wastewater composition parameter specific LCIs. They were calculated for ancillary and energy consumption, for the emission of pollutants into air, and water, and for the generation of sludge. Data presented in the following represent daily average for year 2010.

5.1.5.1. Consumption Factors

Once decided the allocation criteria of every single quantified input in the system under study, was later on possible to calculate the consumption factor for each of the auxiliaries employed and the transfer coefficient of every wastewater composition parameter.

The consumption factor describes the mass, volume or energy content of the auxiliaries used per parameter treated. The relation auxiliary-parameter is perfectly assigned above with the allocation criteria explanation. For the calculation of the consumption factors, it was adapted for the present model an equation previously proposed and utilized by other authors (Köhler, 2006) (Recan, 2005):

$$cf_A = \frac{consumption_A}{mass\ or\ volume_i}$$

Equation 18

Where cf_A makes reference to the consumption factor for the auxiliary A (electrical energy, lime, natural gas, etc.) in the mass or volume of the parameter i (Q, TOC, N, P or H) which generates the auxiliary consumption. Each consumption factor value is reported in the following section (Resulting model).

Because confidentiality reasons, the estimated consumption factors cannot be listed here. However in Table 20 are shown just the percentage of total auxiliary regarding each process parameter considering the entire wastewater treatment system, i.e., all five sub stages described before set together. For example, for the case of the electrical energy, it can be said that 31% of the kWh used in the system is applied per transported cubic meter; 47% per TOC kilogram fed, 19% per N kilogram, 1% per P kilogram; and 3% per H^+ kilogram. The increase or decrease in the input of any of these parameters will modify the electrical utilization quantity, and consequently will have a bigger o smaller impact in the environmental load. Figure 14 illustrates the partitioning of each auxiliary between wastewater composition parameters.

Auxiliary / Parameter	Q		TOC		N		P		H+	
Electrical energy	31%	kWh/ m^3	47%	kWh/kg TOC	19%	kWh/ kg N_T	1%	kWh/ kg P	3%	kWh/ kg H^+
Thermal Energy (steam)	77%	kg/ m^3	17%	kg/kg TOC	4%	kg/ kg N_T	2%	kg/ kg P	-	kg/ kg H^+
Lime	25%	kg/m3	7%	kg/kg TOC	11%	kg/ kg N_T	2%	kg/ kg P	55%	kg/ kg H^+
Fe salts	28%	kg/ m^3	28%	kg/kg TOC	7%	kg/ kg N_T	38%	kg/ kg P	-	kg/ kg H^+
Service water	72%	L/ m^3	22%	L/kg TOC	4%	L/ kg N_T	2%	L/ kg P	-	L/ kg H^+
Polymer	86%	kg/ m^3	10%	kg/kg TOC	3%	kg/ kg N_T	1%	kg/ kg P	-	kg/ kg H^+
Natural gas	12%	L/ m^3	84%	L/kg TOC	4%	L/ kg N_T	-	L/ kg P	-	L/ kg H^+
Anti foamer	-	L/ m^3	-	L/kg TOC	100%	L/ kg N_T	-	L/ kg P	-	L/ kg H^+
6 bar	83%	L/ m^3	13%	L/kg TOC	3%	L/ kg N_T	1%	L/ kg P	-	L/ kg H^+
instrument air	73%	L/ m^3	22%	L/kg TOC	4%	L/ kg N_T	1%	L/ kg P	-	L/ kg H^+
Nitrogen gas	-	L/ m^3	100%	L/kg TOC	-	L/ kg N_T	-	L/ kg P	-	L/ kg H^+
Aluminate	-	kg/ m^3	-	kg/kg TOC	-	kg/ kg N_T	100%	kg/ kg P	-	kg/ kg H^+
Polyaluminum chloride	-	kg/ m^3	-	kg/kg TOC	100%	kg/ kg N_T	-	kg/ kg P	-	kg/ kg H^+
Potable Water	72%	L/ m^3	22%	L/kg TOC	4%	L/ kg N_T	2%	L/ kg P	-	L/ kg H^+
Amidosulfonic acid	22%	kg/ m^3	17%	kg/kg TOC	44%	kg/ kg N_T	2%	kg/ kg P	15%	kg/ kg H^+
HCl (32 %)	43%	kg/ m^3	42%	kg/kg TOC	11%	kg/ kg N_T	4%	kg/ kg P	-	kg/ kg H^+

Table 20. Percentage consuming factors (Almanza, 2012)

Because the particularity of CURRENTA wastewater treatment plant, where the Chempark and municipal effluent have different entry points and treatments (municipal flows directly to Cascade Biology), the consumption factors were considered by sub stage to obtain a real description of the auxiliaries employment. Again, due confidentiality reasons the calculated values are no reported here; instead are presented per sub stage, tables showing the percentage of total auxiliary regarding each process parameter considering the sub division of the wastewater treatment system. In Tables 21 to 25 is presented this information. Note that the percentages mentioned in these tables correspond to a summary of the already explained numbers in section 5.1.

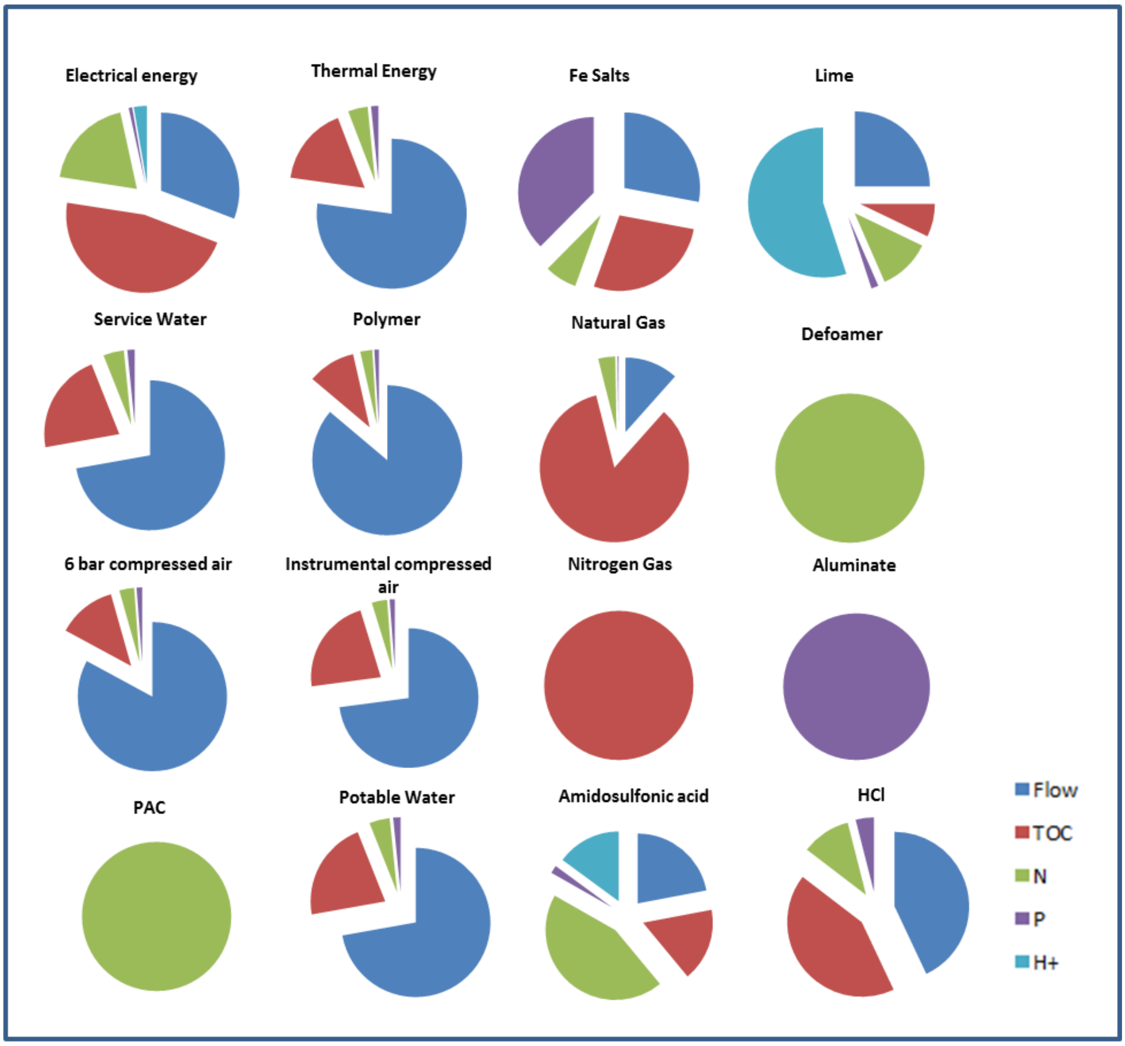

Figure 14. Auxiliaries partitioning between wastewater composition parameters; Units according Table 20. Percentage consuming factors Table 20 (Almanza, 2012).

PRETREATMENT										
	Flow		TOC		N		P		H+	
Electrical energy	84%	kWh/ m^3	0%	kWh/kg TOC	0%	kWh/ kg N_T	0%	kWh/ kg P	16%	kWh/ kg H^+
Thermal Energy	100%	kg/ m^3		kWh/kg TOC		kWh/ kg N_T		kWh/ kg P		kWh/ kg H^+
Lime	24%	kg/ m^3		kg/kg TOC		kg/ kg N_T	1%	kg/ kg P	75%	kg/ kg H^+
Service water	100%	L/ m^3		L/kg TOC		L/ kg N_T		L/ kg P		L/ kg H^+
Natural Gas	100%	L/ m^3		L/kg TOC		L/ kg N_T		L/ kg P		L/ kg H^+
Amidosulfonic acid	24%	kg/ m^3		kg/kg TOC		kg/ kg N_T	1%	kg/ kg P	75%	kg/ kg H^+
6 bar air	100%	L/ m^3		L/kg TOC		L/ kg N_T		L/ kg P		L/ kg H^+
Instrumental Air	100%	L/ m^3		L/kg TOC		L/ kg N_T		L/ kg P		L/ kg H^+
Potable Water	100%	L/ m^3		L/kg TOC		L/ kg N_T		L/ kg P		L/ kg H^+

Table 21. Percentage consuming factors in Pretreatment

TOWER BIOLOGY										
	Flow		TOC		N		P		H+	
Electrical energy	12%	kWh/ m3	57%	kWh/kg TOC	32%	kWh/ kg NT	0%	kWh/ kg P		kWh/ kg H+
Thermal Energy	100%	kg/ m3		kWh/kg TOC		kWh/ kg NT		kWh/ kg P		kWh/ kg H+
Lime		kg/ m3		kg/kg TOC	100%	kg/ kg NT		kg/ kg P		kg/ kg H+
Polymer	100%	kg/ m3		kg/kg TOC		kg/ kg NT		kg/ kg P		kg/ kg H+
Defoamer		L/ m3		L/kg TOC	100%	L/ kg NT		L/ kg P		L/ kg H+
Service water	100%	L/ m3		L/kg TOC		L/ kg NT		L/ kg P		L/ kg P
6 bar air	100%	L/ m3		L/kg TOC		L/ kg NT		L/ kg P		L/ kg H+
Instrumental Air	100%	L/ m3		L/kg TOC		L/ kg NT		L/ kg P		L/ kg H+
Natural Gas	100%	L/ m3		L/kg TOC		L/ kg NT		L/ kg P		L/ kg H+
Aluminate		kg/ m3		kg/kg TOC		kg/ kg NT	100%	kg/ kg P		kg/ kg H+
Potable Water	100%	L/ m3		L/kg TOC		L/ kg NT		L/ kg P		L/ kg H+
Amidosulfonic acid		kg/ m3		kg/kg TOC	100%	kg/ kg NT		kg/ kg P		kg/ kg H+

Table 22. Percentage consuming factors in Tower Biology

CASCADE BIOLOGY										
	Flow		TOC		N		P		H+	
Electrical energy	45%	kWh/ m3	47%	kWh/kg TOC	32%	kWh/ kg NT	3%	kWh/ kg P		kWh/ kg H+
Fe salts		kg/ m3		kg/kg TOC		kg/ kg NT	100%	kg/ kg P		kg/ kg H+
Service water	100%	L/ m3		L/kg TOC		L/ kg NT		L/ kg P		L/ kg H+
Polymer	100%	kg/ m3		kg/kg TOC		kg/ kg NT		kg/ kg P		kg/ kg H+
6 bar air	100%	L/ m3		L/kg TOC		L/ kg NT		L/ kg P		L/ kg P
Instrumental Air	100%	L/ m3		L/kg TOC		L/ kg NT		L/ kg P		L/ kg H+
Nitrogen gas		L/ m3	100%	L/kg TOC		L/ kg NT		L/ kg P		L/ kg H+
Amidosulfonic Acid		kg/ m3		kg/kg TOC	100%	kg/ kg NT		kg/ kg P		kg/ kg H+
PAC		kg/ m3		kg/kg TOC	100%	kg/ kg NT		kg/ kg P		kg/ kg H+
Potable Water	100%	L/ m3		L/kg TOC		L/ kg NT		L/ kg P		L/ kg H+
Lime		kg/ m3		kg/kg TOC	100%	kg/ kg NT		kg/ kg P		kg/ kg H+

Table 23. Percentage consuming factors in Cascade Biology.

WASTE AIR TREATMENT										
	Flow		TOC		N		P		H+	
Electrical energy		kWh/ m3	96%	kWh/kg TOC	4%	kWh/ kg NT		kWh/ kg P		kWh/ kg H+
Service water		L/ m3	96%	L/kg TOC	4%	L/ kg NT		L/ kg P		L/ kg H+
Natural gas		L/ m3	96%	L/kg TOC	4%	L/ kg NT		L/ kg P		L/ kg H+
Instrumental Air		L/ m3	96%	L/kg TOC	4%	L/ kg NT		L/ kg P		L/ kg H+
Potable Water		L/ m3	96%	L/kg TOC	4%	L/ kg NT		L/ kg P		L/ kg H+

Table 24. Percentage consuming factors in Waste Air Treatment

SLUDGE TREATMENT										
	Flow		TOC		N		P		H+	
Electrical energy	43%	kWh/ m3	42%	kWh/kg TOC	11%	kWh/ kg NT	4%	kWh/ kg P		kWh/ kg H+
Thermal Energy	43%	kg/ m3	42%	kWh/kg TOC	11%	kWh/ kg NT	4%	kWh/ kg P		kWh/ kg H+
Lime	43%	kg/ m3	42%	kg/kg TOC	11%	kg/ kg NT	4%	kg/ kg P		kg/ kg H+
Fe salts	43%	kg/ m3	42%	kg/kg TOC	11%	kg/ kg NT	4%	kg/ kg P		kg/ kg H+
Service water	43%	L/ m3	42%	L/kg TOC	11%	L/ kg NT	4%	L/ kg P		L/ kg H+
Polymer	43%	kg/ m3	42%	kg/kg TOC	11%	kg/ kg NT	4%	kg/ kg P		kg/ kg H+
6 bar air	43%	L/ m3	42%	L/kg TOC	11%	L/ kg NT	4%	L/ kg P		L/ kg H+
Instrumental Air	43%	L/ m3	42%	L/kg TOC	11%	L/ kg NT	4%	L/ kg P		L/ kg H+
Potable Water	43%	L/ m3	42%	L/kg TOC	11%	L/ kg NT	4%	L/ kg P		L/ kg H+
Amidosulfonic acid	43%	kg/ m3	42%	kg/kg TOC	11%	kg/ kg NT	4%	kg/ kg P		kg/ kg H+
Natural Gas	43%	L/ m3	42%	L/kg TOC	11%	L/ kg NT	4%	L/ kg P		L/ kg H+
HCl (32 %)	43%	kg/ m3	42%	kg/kg TOC	11%	kg/ kg NT	4%	kg/ kg P		kg/ kg H+

Table 25. Percentage consuming factors in Sludge Treatment

5.1.5.2. Transfer Coefficients

As mentioned before, it is also necessary to establish the partitioning of the inflow wastewater elements among the outflow stream of the system which include the sludge, emission to air and discharge treated water to the receiving water body (Köhler, 2006). To describe this, it was considered the equation below (Köhler, 2006) (Seyler, Hofstetter, & Hungerbühler, 2005) :

$$tc_{i,j} = \frac{A_{i,j}}{A_{i,w}}$$

Equation 19

Where $tc_{i,j}$ is the transfer coefficient of the element i to the output j, tc is dimensionless (percentage); $A_{i,j}$ is the element flow of the parameter i via the output j in kg/d; $A_{i,w}$ is the parameter flow of the element i in the average wastewater input in kg/d. To completely describe the process system there must be one transfer coefficient for every wastewater composition parameter which cause pollution in the environment: TOC ($tc_{i,TOC}$), N_T ($tc_{i,N}$), P_T ($tc_{i,P}$) and H^+ ($tc_{i,H}$). For the parameter "Q" is not worth considering a transfer coefficient, because even when it is known it is partitioned through the air (Evaporation), sludge (moisture content) and water, it does not signify an environmental load.

In Table 26 the transfer coefficients considering the entire wastewater treatment system are presented for the emission to water, emission to water, and sludge to incinerator plant; Table 27 shows the transfer coefficients separately per sub stage, taking in to account the intermediate steps, where the transfer is done not directly to the environment, but to the immediate following sub stage according to the diagram flow.

Pollutants in the wastewater input	Emission to water	Emission to Air	Sludge to Inc
TOC	11,75%	37,06%	51,18%
N	18,11%	48,77%	33,14%
P	6,95%	0,00%	93,05%
H+	0,00%	0,00%	100,00%

Table 26. Transfer Coefficients considering the entire wastewater treatment system

For the carbon compounds, expressed as TOC, it can be appreciated from Table 26 that not all organic matter is removed from the wastewater and some pollution remains in the effluent (11,75%). A portion of the removed organic matter goes to the air (37,06%) and other portion to the sludge (51,8%). The TOC remainder in the water was calculated with the effluent quality data available. The transfer to air and sludge respectively was calculated adapting sludge fraction proposed in previous research (Doka, 2009) where they assume that the removed carbon has a distribution of 58% to sludge and 42% to air as CO_2. Table 26 demonstrates that 86% of the TOC treated in the Tower biology is eliminated, while around 68% of Cascade Biology is extracted. Preliminary clarification removes around 25% of TOC.

Pollutants in the wastewater input	PT	TB	CB	WA	ST
	Emission to Water				
TOC	75,00%	14%	32,62%	0,00%	0,00%
N	61,86%	23%	34,89%	0,00%	0,00%
P	72,47%	16,38%	8,40%	0,00%	0,00%
H+	0,00%	0,00%	0,00%	0,00%	0,00%
	Emission to Air				
TOC	0,00%	36,05%	28,30%	100,00%	0,00%
N	0,00%	53,14%	50,65%	100,00%	0,00%
P	0,00%	0,00%	0,00%	0,00%	0,00%
H+	0,00%	0,00%	0,00%	0,00%	0,00%
	Sludge to incinerator				
Q					
TOC	25,00%	49,78%	39,08%	0,00%	100,00%
N	38,14%	24,05%	14,46%	0,00%	100,00%
P	27,53%	83,62%	91,60%	0,00%	100,00%
H+	100,00%	0,00%	0,00%	0,00%	100,00%

Table 27. Transfer Coefficients in terms of each sub stage

In the case of phosphorous it was recognized that all the phosphorous eliminated in the wastewater is completely transferred to the sludge and transfer to air is negligible (Doka, 2009). It can be seen in Table 26 that a good removal is achieved transferring to the water just 6,95 % of the total phosphorus present in the influent.

Nitrogen flow through the WWTP is complicated by the fact that nitrogen is present in many different forms that can be converted into each other during each of the stages of the whole process (Doka, 2009). To simplify the nitrogen transfer coefficient estimation the nitrogen speciation was ignored and was just considered the total removal as total nitrogen. To calculate nitrogen transferred to air it was assumed that all the nitrogen removed in the biological stages by nitrification-denitrification, except an assumed 5% which is assigned to biomass build up, is converted to nitrogen gas (46%). It was also included within the air emission the theoretical N_2O produced which was calculated according to the suggested generation factor of 0.006 – 0.253 $kgN_2O\text{-}N/kgN_{de}$ proposed by Foley for advanced biological WWTP (Foley & Lant, 2009). The buildup assigned nitrogen was contemplated as the nitrogen transmitted to the sludge.

H^+ is practically all removed with the sludge in the pretreatment sub stage after the lime neutralization, so 100% of H+ is transferred to the sludge and no remainder considered to be transported to air or water.

5.2. Background system

The background system is that which supplies energy and materials to the foreground system (core process), usually via a homogeneous market so that individual plants and operations cannot be identified (Azapagic & Clift, 1999). In this case, background systems make reference to construction phase; energy (Electric, thermal, compressed air and Natural gas); supply of auxiliary materials (Lime, Fe salts, aluminate, etc); and treated sludge incineration. Construction was only considered for energy consumption comparison purposes from available data in Currenta records. The other systems were calculated from databases provided by Umberto which are represented by data for a mix or a set of mixes of different technologies or processes.

5.2.1. Construction phase

As mentioned in section 4.2, a rough consideration for the construction phase was done to make an approximated comparison against the foreground system. This comparison was conducted as an energy analysis for the tower and cascade biology tank construction considering energy in material, energy in delivery and energy on-site work.

Energy is required during the construction phase for the production of materials, their delivery to site, and construction (Emmerson, Morse, Lester, & Edge, 1995). In the present approximation it was only considered steel and concrete needed (from Currenta records) to the construction of the 4 towers biologies, the secondary clarifiers and the cascade basins. Material production energy information was obtained from a review of literature (247 kWh/ton concrete; 6.600 kWh/ton steel) (Norgate, Jahanshahi, & Rankin, 2004) (Umwelt Bundesamt, 2012). Energy required to delivery materials and for on-site construction were estimated using proportional factors from Emmerson (Emmerson, Morse, Lester, & Edge, 1995). The total energy estimation was normalized to daily consumption in kWh considering a lifetime of 40 and 35 years for the tower and cascade tanks respectively.

In this way was possible to compare the calculated total energy use during the construction phase against the total energy use in the operation phase on a daily basis (kWh/d). The result of this comparison demonstrate that the energy use in the operation phase is much higher than the construction (94,2 vs 5,8%), so that in long long-lived installations the construction phase is of less importance. This affirmation coincides with numerous related studies where it has been demonstrated that the impact in the construction phase is much lower than the operation (Gallego, 2008). Within this context, the present study includes only the operation of the studied technical systems, excluding further details in the construction phase.

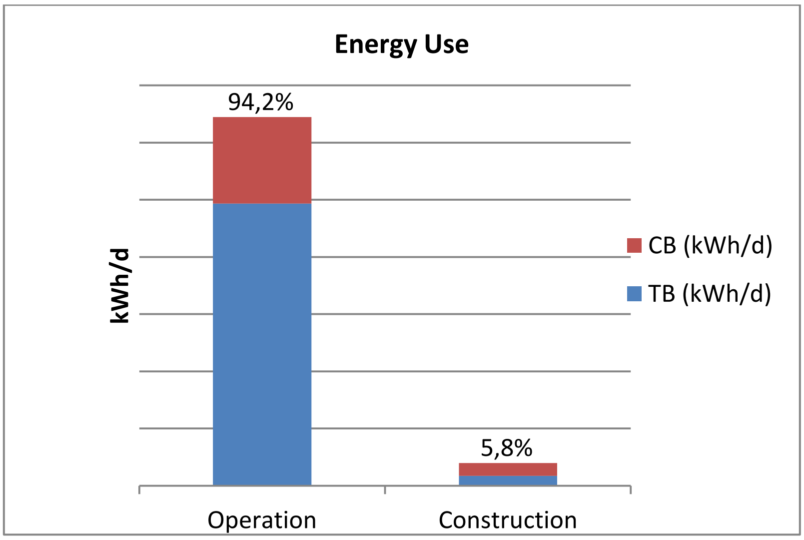

Figure 15. Energy use comparison between Operation and Construction

5.2.2. Energy Supply

The energy consumption comprises the use of electricity, compressed air and natural gas. In addition, steam is used for heat supply.

Electricity generation is the process of producing electric energy from other forms of energy (kinetic energy). An uninterrupted electricity supply is essential for any process to maintain productivity at the highest possible level. In Currenta WWTP, the electricity demand is achieved through the factory power plant supply and electricity purchase on the free market (Kolisch, 2012). The expenses for the production and supply of electricity were calculated with databases provided by Umberto according to the mix presented in Table 28. This mix is derived from Currenta energy reports (CURRENTA, 2012).

Electricity-Mix Chempark	
Energy Source	**Proportion**
Nuclear Power	9%
Coal	33%
Natural Gas	50%
Other fossil fuels	2%
Renewable Energy	7%
Total	100%

Table 28. Electricity Mix Chempark

The supply of thermal energy is done through steam and natural gas. A portion of the natural gas used serves simultaneously to operate the waste air treatment incinerator which corresponds to 85% of the total fed (Almanza, 2012). Both steam and natural gas were calculated with databases provided by Umberto. For steam was contemplated the mix presented in Table 29 (CURRENTA, 2012).

Steam-Mix Chempark	
Energy Source	**Proportion**
Coal	28%
Natural Gas	71%
Other fossil fuels	1%
Total	100%

Table 29. Steam Mix Chempark

Compressed air is indispensable in production processes. In Currenta WWTP is provided 3 bar compressed air for aeration and circulation of the tower biologies 1-4. Additionally there is a 6-bar compressed air network that usually serves as operating pressurized air. The production of this compressed air was also considered as background process and estimated with Umberto.

5.2.3. Auxiliary Materials supply

In section 5.2 where the foreground system was analyzed, it was also presented the usage of many auxiliary materials that helps Currenta WWTP achieve its depuration purposes (Table 8). To consider the upstream processes of the production of these auxiliary materials Umberto databases were consulted. Nevertheless, some limitations were found in the characterization of these upstream processes. In Table 30 are presented briefly the consideration made for each material (ECOINVENT, 2009).

Material	Source	Process considerations	Limitations
Lime	Ecoinvent V 2.1	Includes the calcination process. Also included is the electricity consumption for preheating of the heavy fuel oil and one part of the total heating energy for "production" and "administration". Only the measured emissions are included.	Geography; module calculated with operation data from Switzerland
Fe Salts	Ecoinvent V 2.1	Production of Fe salts solution from scrap iron, spent pickling acids, hydrogen chloride and chlorine. Process electricity demand included.	Geography; module calculated with operation data from Switzerland
Polymer	-	Not specific process available	-
Defoamer	-	Not specific process available	-
Aluminate	-	Not specific process available	-
PAC	-	Not specific process available	-
Amidosulfonic acid	-	Not specific process available	-
HCl	Ecoinvent V 2.1	This report assumes that HCl is generated from combustion of chlorine with hydrogen. Supplies and emissions included.	Module calculated with average operation data from Europe
NaOH	Ecoinvent V 2.1	This report assumes that NaOH is generated by electrolytic chloralkali process. Supplies, coproducts and emissions are included within the module.	Module calculated with average operation data from Europe

Table 30. Databases considered for auxiliary materials

Also transport processes for these materials were taken in account; for this it was used also the respective Umberto dataset for truck transport. Only the transport distance and the cargo weight were adjusted depending on the respective transport process in the system. In Table 31 distance are given depending on the supplier.

Material	Supplier Location	Distance (km)
Lime	Wülfrath, Germany	43
Fe salts	Leverkusen, Germany	5
Polymer	Krefeld, Germany	60
Defoamer	Leverkusen, Germany	5
Aluminate	Lünen, Germany	93
PAC	Rotterdam, Holland	270
Amidosulfonic Acid	Mülheim, Germany	63
HCl	Leverkusen, Germany	5

Table 31. Auxiliary supplier distance regarding Currenta WWTP

5.2.4. Incinerator

The filter cake outgoing the Sludge treatment plant in both scenarios is disposed of in the sewage sludge incineration plant. To describe this Currenta WWTP downstream process was used an Umberto database for a municipal wastewater sludge incineration plant. This database estimates the demand for auxiliary material and energy, the emissions and residues, and the thermal energy, considering a heating value of 4.26 MJ/kg, derived from the incineration of dewatered sludge with around 30% total solids (ECOINVENT, 2009).

CHAPTER 6. RESULTS

This chapter exposes the final results of the present Life Cycle Assessment which comprises the life cycle inventory (LCI) and the Life Cycle Impact Assessment (LCIA). Also discussion and analysis of relevant findings are included within this chapter to establish the study interpretation.

6.1. Life Cycle Inventory results

The application of the Life Cycle Inventory model described in chapter 5 results in the generation of a large amount of data that describes the whole system considered (Foreground and Background). For the present LCI Umberto software was used as a tool to estimate the material and energy balances for the processes under study. Consumption factors and transfer coefficients set in the model in chapter 5, as well as the inlets in terms of the main parameters, were entered in the software to produce the inventory. Once the inventory was produced, the relative importance of the inputs and outputs from the different processes in relation to each other and the functional unit was appreciable.

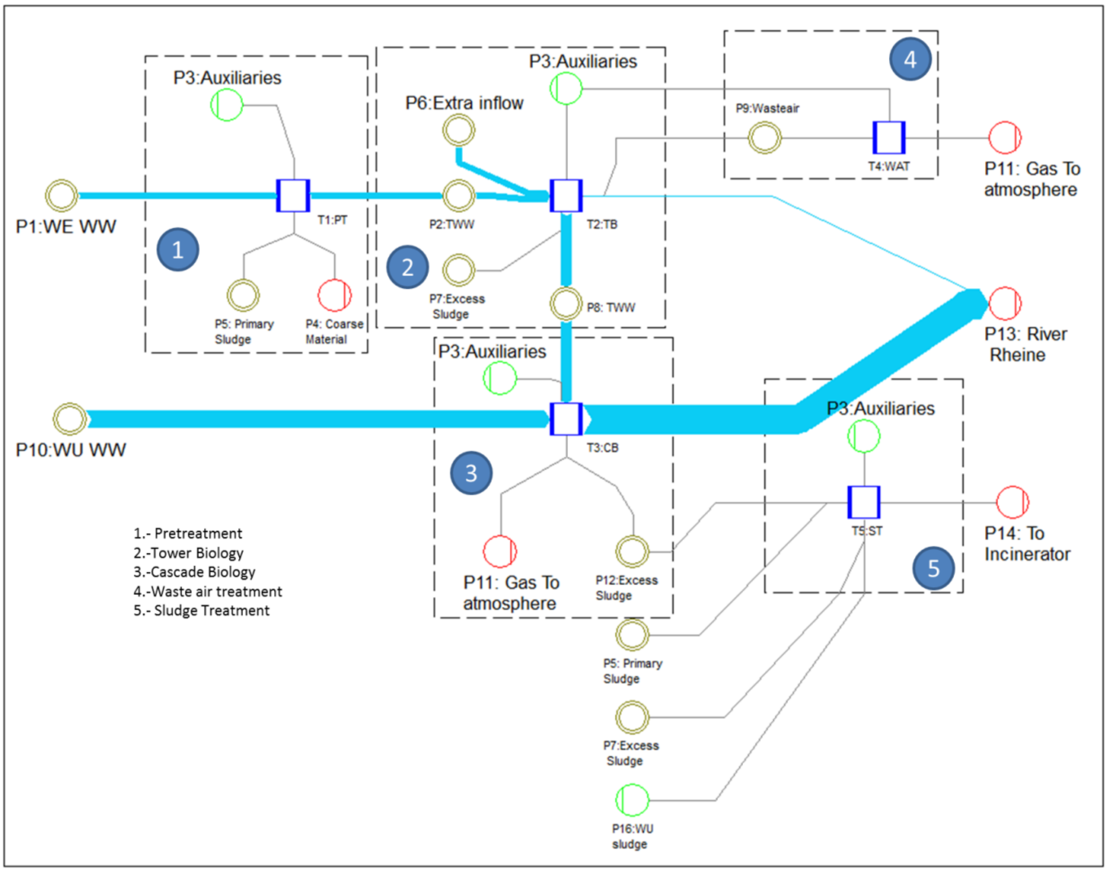

Figure 16. Currenta flow diagram within Umberto. Wastewater volumes.

Because the large number of materials and confidentiality agreement with Currenta, the resulting inventory values are not reported in this study. In Figure 16 and Figure 17 are just shown in Sankey diagrams the flow of the main parameters through each sub stage of the foreground system for the current operation mode within Umberto platform. Nevertheless, the complete resulting inventory values are the basis for Life Cycle Impact Assessment shown in the next section.

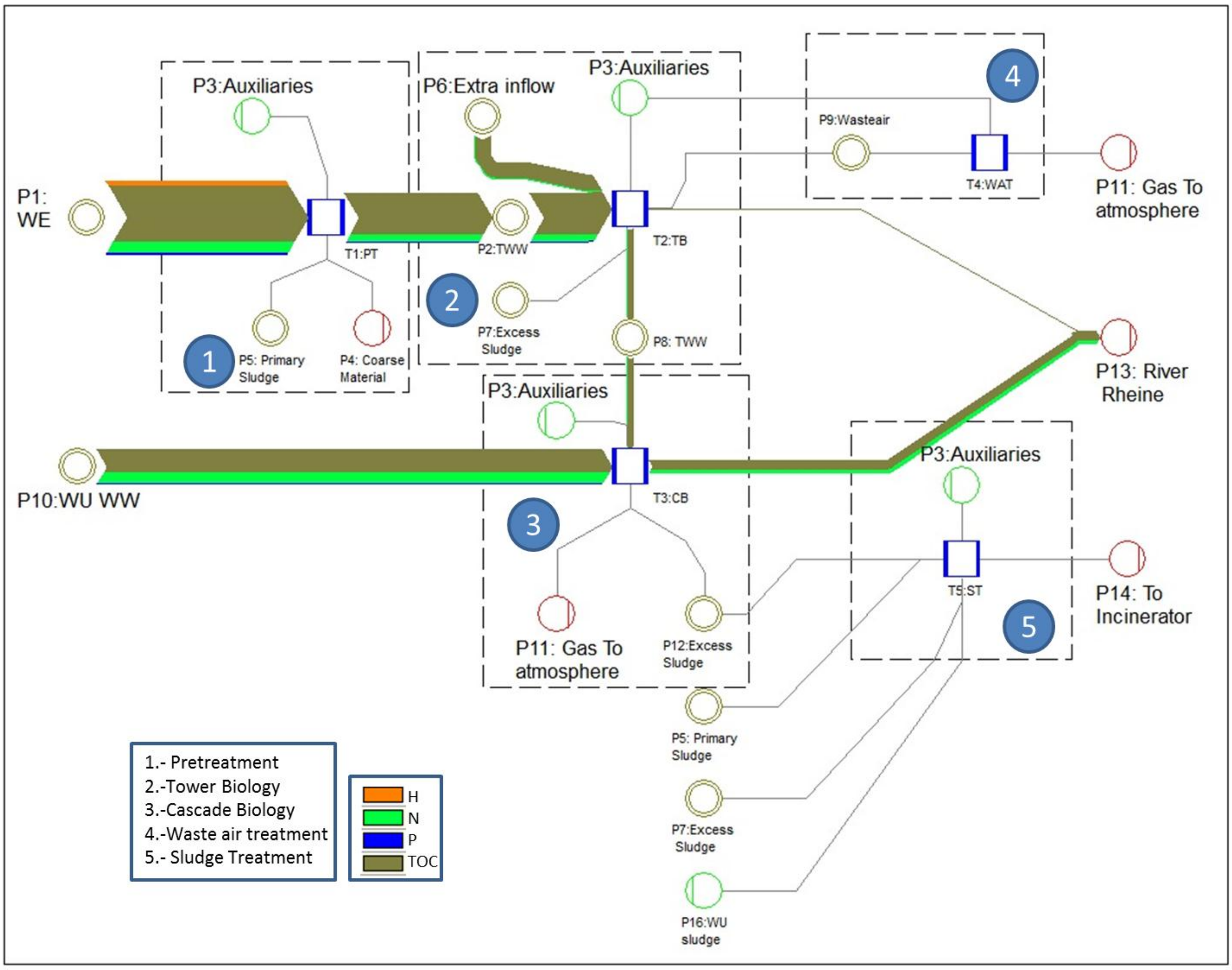

Figure 17. Currenta flow diagram within Umberto. Main parameters

6.2. Life Cycle Impact Assessment Results

The Life Cycle Impact assessment is the phase of an LCA that evaluate the significance of potential environmental impacts using the results of the life cycle inventory. To achieve this, all inputs and outputs are related to categories that quantify the impacts. In the present work, the LCIA was conducted using the CML baseline method (CML baseline 2000) provided in Umberto software. This method comprises 14 impact categories, of which were selected 9 in order to fully describe the system under study emissions. In the following sections firstly is given the environmental profile of the Currenta WWTP under its actual conditions, and secondly is explained the contrasting comparison with the planned sludge digestion scenario.

6.2.1. Currenta Wastewater Treatment plant present status

One of the purposes of the present LCA is to analyze the present environmental performance of Currenta's Wastewater treatment process to determine its present status and to enable future improvements (chapter 4). To fulfill this purpose in this section the analysis is presented and discussed. This first evaluation is not aimed to make any comparisons but to identify critical parameters for each process in terms of LCA impact categories. This way, priorities internally in Currenta can be defined for further optimizations.

The environmental profile was calculated with regards to the input and output data using the CML baseline methodology. The overall environmental profile is given in Table 32.

Impact	Value	Unit
Abiotic depletion resources	0.00116118	kg Sb eq
Global warming	1.14559364	kg CO_2 eq
Acidification	0.001036908	kg SO_2 eq
Eutrophication	0.008570426	kg PO_4 eq
Freshwater aquatic ecotoxicity	0.000162126	kg p-DCB
Freshwater sedim. ecotoxicity	0.000350965	kg p-DCB
Human toxicity	0.014391331	kg p-DCB
Odour	12.14740884	m^3
Terrestrial ecotoxicity	5.0193E-05	kg p-DCB

Table 32. Currenta WWTP overall environmental profile (present scenario)

To read Table 32 is important to note that each impact has a distinct unit (see unit column in Table 32), so is not possible to prosecute cross comparisons between categories (Köhler, 2006). Therefore normalization was applied in order to obtain a single impact score in a particular chosen unit to later have a better understanding of the relative magnitude for each indicator result. For the present study normalization was carried out in relation to the latest available emission data for Germany (Remy, 2010). The normalized unit was then pe*a in Germany. Freshwater sediment ecotoxicity and odour were not normalized because lack of data. In the Table 33 below are given the normalized values for each impact category. The graphic of the Figure 18 shows these normalized values too but schematically represented.

Impact	Normalized value	Unit
Abiotic depletion	3,5619E-05	pe*a
Global warming	9,3886E-05	
Acidification	7,6808E-05	
Eutrophication	0,00131853	
Freshwater aquatic ecotoxicity	1,8237E-06	
Human toxicity	1,9806E-06	
Terrestrial ecotoxicity	7,1602E-07	

Table 33. Normalized values of the impact categories in pe*a

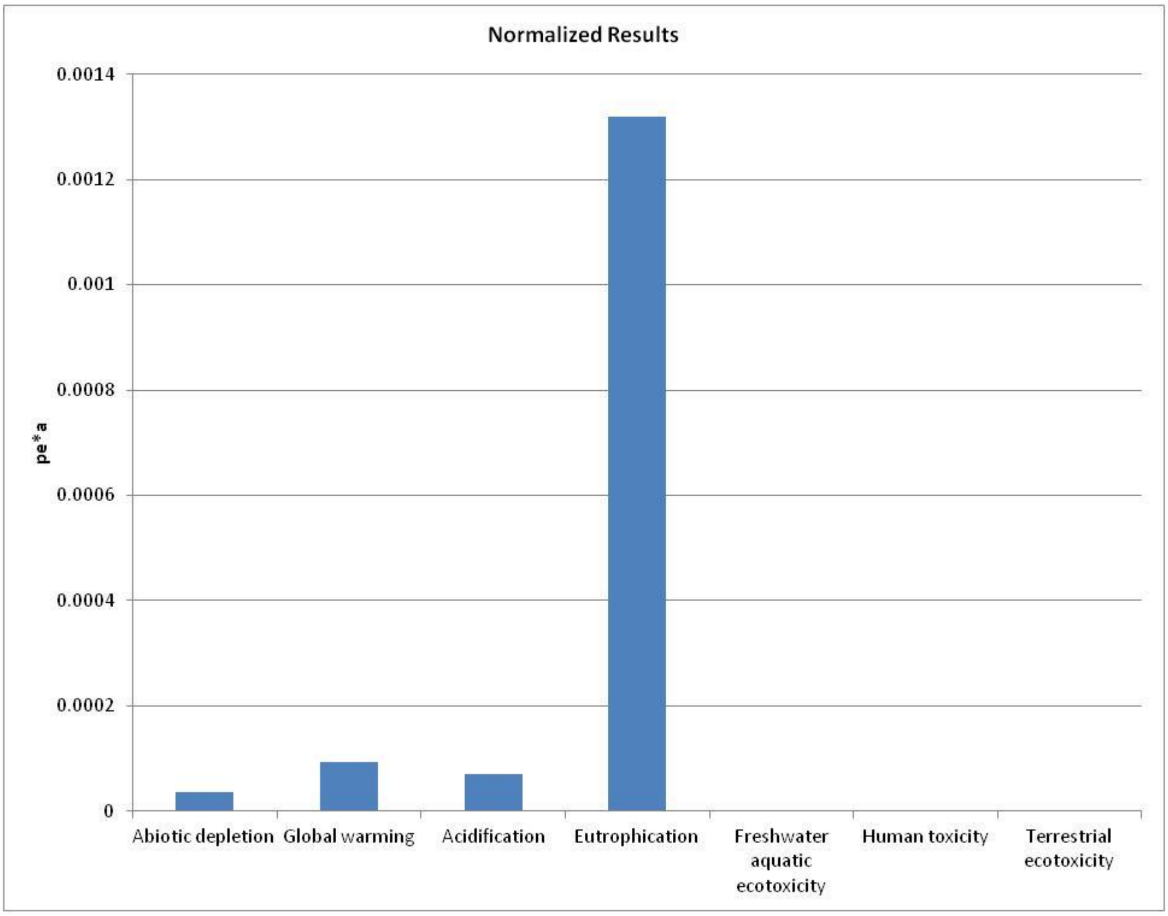

Figure 18. Normalized values of the impact categories in pe*a

According to the normalization criteria considered, it can be said that the normalized value of 1 pe*a inhabitant equivalent is equal to 100% of the total environmental impact in the entire country of Germany; this means for example that for the abiotic depletion value the impact contribution of Currenta WWTP for the whole country is of 0.004%.

Schmitz and Paulini defined an impact specific contribution scale in terms of the total value to broadly interpret the magnitude of a given impact (Schmitz & Paulini, 1999). In this scale they specified every value below 20% of the maximum value as very low. According to this scale the contribution of all indicators for the present study are very low, all under 1% of the total in Germany.

Hence it can be said that Currenta WWTP has an insignificant share of the total impact categories demand in Germany. Eutrophication was the highest with a normalized value of 0.13%. This was expected since this category describes mainly COD, and nutrients released to the environment, which are the main elements that are intended to be removed within the treatment. These elements are highly concentrated in the inlet of the process and even when they are reduced considerably, the removal is not of 100%.

In the next paragraphs below a disaggregation of each indicator is done to better understand this resulting environmental profile: First an analysis in terms of the main parameters Q, TOC, N, P and H is accomplished; then another one in regards of the contribution of specific processes is completed (the auxiliaries production, energy supply, WWTP operation and Incineration); and finally one in terms of the 5 sub stages of the foreground system.

As defined in section 4.3, the functional unit was set in regards Hydraulics (Q), Total Organic Carbon (TOC), Total Nitrogen (N), Total Phosphorus (P) and Hydrogen (H^+). Later in chapter 5 the allocation model was presented also in basis of these 5 parameters. As a result, the environmental profile now can be explained in terms of Q, TOC, N, P and H as well. With this, it can be perfectly identified which parameter is more or less responsible of a given impact category result. In the graphic of Figure 19 is given each impact category evaluated in the present study in terms of each of the already mentioned parameters. Here is important to note that, even when the 5 parameters were considered as functional unit to take into account the waste water composition, the referring base to make all calculations was 1 m^3 of treated wastewater in 2010.

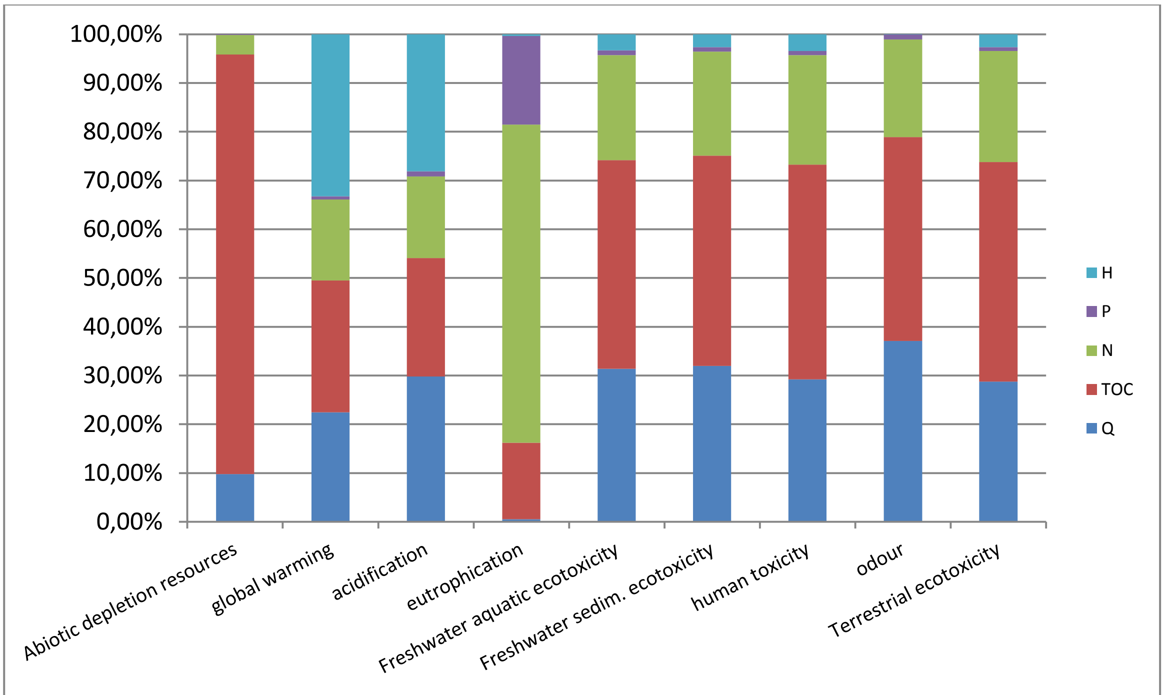

Figure 19. Impact categories results in terms of the 5 main operational values.

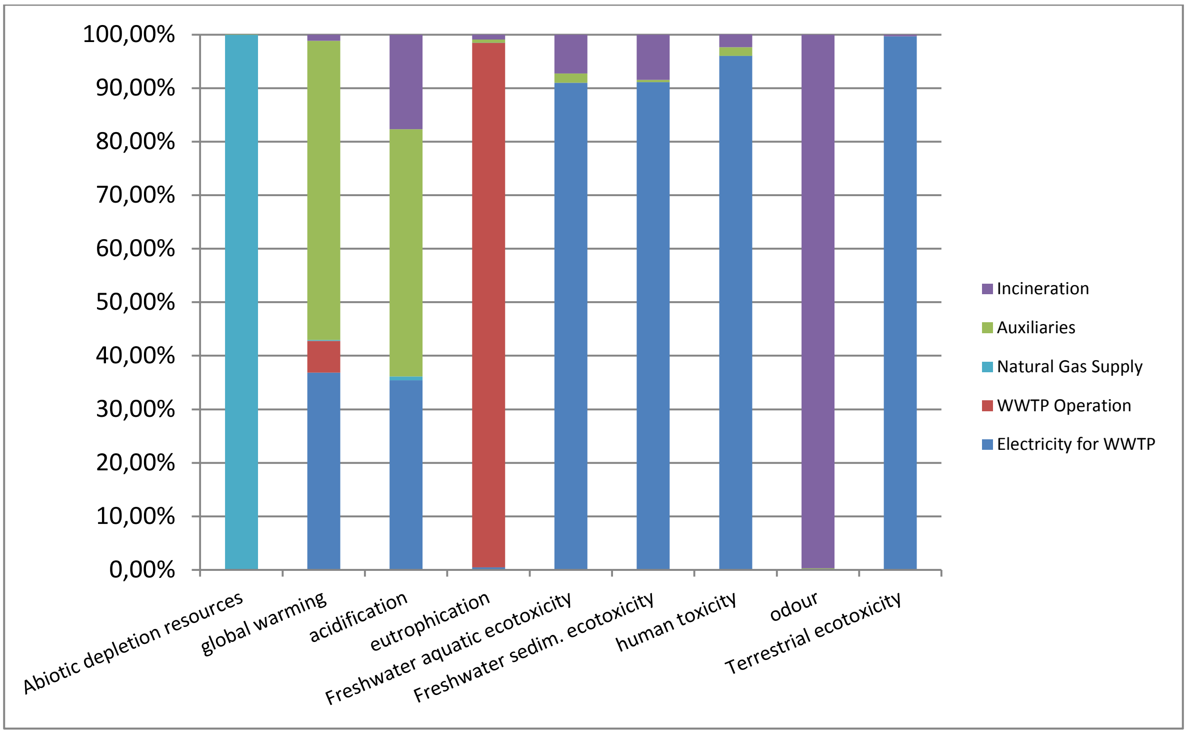

Figure 20. Impact categories results in terms of the processes involved.

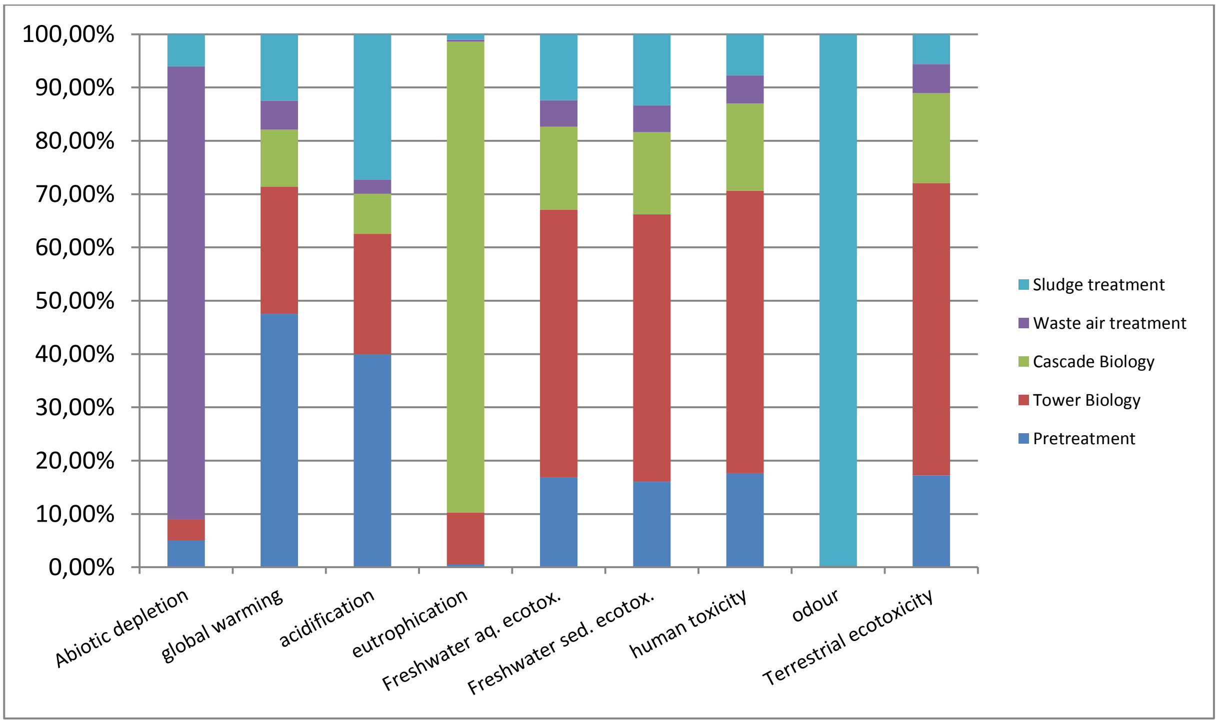

Figure 21. Impact category results in terms of the 5 sub stages of the foreground system.

Additionally is possible to identify critical subsystems in terms of impact categories within the system boundaries considering foreground and background processes. For this purpose Figure 20 shows, for each defined process (Incineration, Energy supply, Natural Gas supply, Auxiliaries production, and WWTP operation), the disaggregated values of the impact categories so that the relative contribution of each one can be analyzed. Moreover in Figure 21 is given the distribution of the impact result regarding the 5 sub stages of the operational stage. In these graphics every impact indicator is expressed as 100%, being the contribution of a process a fraction of this figure.

6.2.1.1. Abiotic depletion

Abiotic depletion makes reference to natural resources (including energy resources) which are regarded as nonliving (Guinée, et al., 2001). In this study it can be appreciated that for the abiotic depletion around 86% of the total is due the TOC inlet concentration, 9.8% due to hydraulics, 4% due to Nitrogen and <1% due to Phosphorous (Figure 19). At the same time from Figure 20 it can be deducted that almost 100% (99.99%) of this impact is because the Natural Gas supply process. This is attributed to the fact that 85% of the total Natural gas consumed in the plant is to operate the incinerators of the waste air treatment stage and the 15% remaining for heating purposes (Figure 21). The quantity of natural gas needed in the waste air treatment, as was described in Table 17 of section 5.1.3, depends in 96% of the TOC concentration in the inflow of the tower biology. The contribution of minerals (Ca for lime and Fe for irons salts) is negligible accounting for less than 0.0001% of the total.

6.2.1.2. Global Warming

Global Warming is defined as the impact of human emissions on the radioactive forcing of the atmosphere (Guinée, et al., 2001). For this impact the share regarding the parameters is around 27% of the total due the TOC inlet concentration, 22% due to hydraulics, 17% due to Nitrogen, <1% due to Phosphorous and 33% because H+. In terms of the causative process (Figure 20) the highest contributor are auxiliaries production and transportation background processes with 56% of the total (highly influenced by the CO_2 emitted by the lime kiln in lime production); later comes with 37% the energy supply; the WWTP operation with 6%, the sludge incinerator with around 1% and then with <1% the Natural Gas supply.

TOC contribution is mainly explained firstly because the N_2O released to the atmosphere in the Waste air treatment stage which in a 96% is caused by inlet TOC and 4% by the inlet N; secondly because the emissions (CO_2, N_2O and CH_4) of the upstream processes to produce the electricity necessary to its treatment (47% of the total for aeration)(See Figure 20); thirdly in a minimum degree due to the incineration emissions where some sludge generated because the TOC is burned (42% of the total).

The 22% of the hydraulics is defined primarily because the emissions (CO_2, N_2O and CH_4) of the upstream processes to produce the electricity necessary for the pumping; and in a smaller manner because the greenhouse emissions generated in producing and transporting the auxiliaries that in the allocation criteria were assigned to the flow (general consumption without attributable causality). Another fraction is also due to the sludge incineration emissions (solids with unidentifiable causality were assigned to hydraulics as default).

Nitrogen (17%) contribution is justified in a way, as for TOC, because N_2O released to the atmosphere in the Waste air stage. Electricity production emissions (CO_2, N_2O and CH_4) also contribute in an import manner taking into account that 19% of the total electricity consumption is function of the inlet “N” concentration. Incineration emissions where sludge generated because the N is burned (11%) add value to this parameter. Auxiliary production and transporting greenhouse emission of the materials assigned to “N” in the allocation model also confer some magnitude to the total result.

Phosphorous small proportion in the global warming share (<1%) is explicated principally with the greenhouse emissions generated in producing and transporting auxiliaries like aluminate and Fe Salts that are used specifically in the treatment to remove phosphorous.

Hydrogen ions load contribution to the global warming category resulted the highest with 33%. This almost exclusively because the greenhouse gases (CO_2, N_2O and CH_4) generated in the production (lime kiln) and transportation of the lime (See proportion of global warming impact for auxiliaries in Figure 20); which is supplied to the treatment to neutralize the wastewater pH.

6.2.1.3. Acidification

Acidification is defined by the emissions of acidifying gases like NH_3, NO_x, and SO_2. In terms of the parameters acidification category is composed as it can be read in Figure 19 as follows: Around 24% of the total due the TOC inlet concentration, 30% due to hydraulics, 16% due to Nitrogen, 1% due to Phosphorous and 28% because H+. Regarding processes again auxiliaries production and transportation background processes is the highest contributor with lime production as main responsible of sulfur dioxide and NO_x emissions. Electricity supply and Incineration emission follow the “auxiliaries” with 35% and 18% respectively.

As in the case of global warming, in terms of parameters, the highest contribution is H with 28% of the total due to the lime production and transportation acidifying emissions. This are caused to supply lime to the pretreatment to neutralize the wastewater pH. In Figure 21 is possible to see the specific causality for acidification of each sub stage. Here, the high influence of the pretreatment sub stage, the most demanding lime consumer, can be appreciated.

6.2.1.4. Eutrophication

Eutrophication describes COD and nutrients released to the environment, so the decisive process here is the treatment of wastewater and the associated effluent loads of nutrients. This can be appreciated in Figure 20 where 98% of the category is d identified in the operation of the WWTP concept. Here is important to emphasize that this impact is not caused directly by the activities in the WWTP operation but by the original pollutant load that comes in the inlet and is not completely removed during the treatment. Small contribution from discharges (nitrogen gases mainly) in incineration, electricity supply and auxiliaries processes can be detected but they are minimal. The bar graphic in Figure 21 clearly shows how the main effluent takes place in the cascade biology.

In addition in Figure 19, where eutrophication results in terms of the 5 main operational values is shown, it can be recognized that the impact distribution is among TOC, N and P (16%, 65% and 18% respectively), which represent the portion of organic matter and nutrients that were no fully removed from the effluent and therefore released to the river Rheine. Nitrogen signifies the highest contributor here because this nutrient has lower elimination ratio (82%) in comparison with TOC (88%) and P (93%).

6.2.1.5. Freshwater ecotoxicity (aquatic and sediment)

This impact category covers impact of toxics substances on aquatic and sediment ecosystems. Direct ecotoxicity TOC emissions were not considered within this study because lack of data. Regarding causative process (Figure 20), these toxic substances are principally released with a proportion of around 91% by the electricity supply background processes. So, in terms of the main parameters, the total share is closely related with those parameters for which is needed more energy. Within this context TOC, the element which utilizes most of the energy to its removal, is the main causer with 43% of the impact category total. In second places comes the hydraulics (2nd energy consumer) with 32%, followed by “N” with 21%, “H” with 3%, and “P” with around 1%.

At lower degree with 7% of the released toxic substances, the sludge incineration also gives some value to the total category result. This is linked with the parameters in proportion of the sludge production of each one (TOC 42%, Hydraulics 43%, Nitrogen 11%, and Phosphorous 4%).

Finally 2% of the ecotoxocity is given by auxiliaries production and transportation background processes.

6.2.1.6. Human Toxicity

Human toxicity covers the impacts on human health of toxic substances present in the environment. In general, electricity supply background processes contribute substantially to this indicator (96%). Minimal share is caused by Auxiliaries and Incineration processes (approx. 2% each). Consequently, as for ecotoxicity categories, in terms of the main parameters the total distribution is closely related with those parameters for which is needed more energy: around 45% of the total due the TOC inlet concentration, 29% due to hydraulics, 22% due to Nitrogen, 1 % due to Phosphorous and 3% because H+.

6.2.1.7. Odour

Odorous substances at a given concentration can become unpleasant. This impact category describes these kinds of substances above that concentration. In the present study, the process which absolutely contributes to this indicator is the sludge incineration emitting substances to the air like ammonia, acetaldehydes, mercaptans, etc. (Figure 20). The incineration operation is totally dependent to the amount of sludge generated in the WWTP, so the category share in terms of the parameters is proportional to the quantity of sludge that each parameter produces: 41% of the total due the TOC inlet concentration, 37% due to hydraulics, 20% due to Nitrogen, and 1 % due to Phosphorous.

6.2.1.8. Terrestrial toxicity

Terrestrial toxicity is another category for ecotoxicity that evaluates toxic impacts on the terrestrial ecosystem. It is strongly determined by the transfer of heavy metals to soil. In the present case these heavy metals discharges are generated (99.7%) in the electricity supply background processes (Figure 20). Minimal quantities are produced in the incineration (0.03%). Then after in terms of the main parameters the total distribution is related with those parameters for which is needed more energy: around 45% of the total due the TOC inlet concentration, 29% due to hydraulics, 22% due to Nitrogen, 1 % due to Phosphorous and 3% because H+.

6.2.2. Present and future scenario comparison

Now in this section the actual Currenta WWTP environmental profile is contrasted with the future scenario where sludge digestion is included (described in chapter 2). To keep the line followed in the last section (6.2.1), and make the approach easier to accomplish, first general results are presented; then each environmental profile to be compared is disaggregated in terms of the main parameters (Q, TOC, N, P and H) and in terms of the relative contribution of the foreground and background processes.

The cumulative results for the comparison of the two Currenta scenarios are presented in Table 34. Here the environmental profile of each one is shown in terms of the chosen CML categories.

	Digester	Current	Units
Abiotic depletion	0,000542472	0,001161175	kg Sb eq
Global warming	1,149793654	1,14559364	kg CO_2 eq
Acidification	0,001003502	0,001036908	kg SO_2 eq
Eutrophication	0,008555359	0,008570426	kg PO_4 eq
Freshwater aquatic ecotoxicity	0,000168744	0,000162126	kg p-DCB
Freshwater sedim. ecotoxicity	0,000364518	0,000350965	kg p-DCB
Human toxicity	0,015170908	0,014391331	kg p-DCB
Odour	9,609296917	12,14740884	m^3
Terrestrial ecotoxicity	5,32577E-05	5,0193E-05	kg p-DCB

Table 34. Overall environmental profile of the two scenarios compared.

From a general perspective, in this table the impact categories values of abiotic depletion, acidification, eutrophication and odour demonstrate that the planned future scenario with sludge digestion preforms better. However, in the impact categories global warming, Freshwater aquatic ecotoxicity, Freshwater sediment Ecotoxicity, Human Toxicity and Terrestrial ecotoxicity, the future scenario seems to be at disadvantage.

To have a better appreciation of the relative magnitude for each indicator result in both scenarios, normalization was also applied in this section to carry out the comparison. The same criterion mentioned in the last section was used to normalize the categories: person equivalent per year in Germany. Table 35 shows the results.

	Digester	Current	Unit
Abiotic depletion	1,66402E-05	3,56189E-05	pe*a
Global warming	9,42299E-05	9,38857E-05	
Acidification	6,8733E-05	7,10211E-05	
Eutrophication	0,001316209	0,001318527	
Freshwater aquatic ecotoxicity	1,89814E-06	1,82369E-06	
Human toxicity	2,08793E-06	1,98064E-06	
Terrestrial ecotoxicity	7,59738E-07	7,1602E-07	
Total	0,00150	0,00153	

Table 35. Normalized environmetal profiles of each scenario compared.

As this table above shows, the overall result value in pe*a of the scenario with sludge digestion scores slightly better. The reasons of better or worse environmental performance per impact category in each scenario are explained below.

6.2.2.1. Abiotic Depletion

As was mentioned in the last section, the main responsible of this impact category is the demand for natural gas used for heating (15%) and as fuel in the waste air treatment incinerator (85%). With sludge digestion, a considerable amount of methane, which represents revenue to the process, is produced. This methane production was deducted from natural gas supply volume to quantify the profit in the contrasting scenario. For this reason it can be appreciated in Figure 22 and Figure 23 that this abiotic depletion category is reduced by half in the scenario with sludge digestion.

Also one of the big benefits that give the sludge digestion is a considerable reduction in the biosolids to be burned in the incinerator. This reduction causes as well a decrease in the consumption of 2 of the most demanding auxiliaries in the process: Iron salts and lime. Nevertheless the benefit from decreasing these auxiliaries is not reflected in the overall value because the characterization factors for abiotic depletion of calcium and iron are too low to show this effect in the present indicator category (Guinée, et al., 2001).

The same allocation model designed in chapter 5 was used in both scenarios. For this reason the contribution proportion in terms of parameters stay the same, i.e., the scenario with sludge digestion decreases proportionally by around half in each parameter (Figure 22).

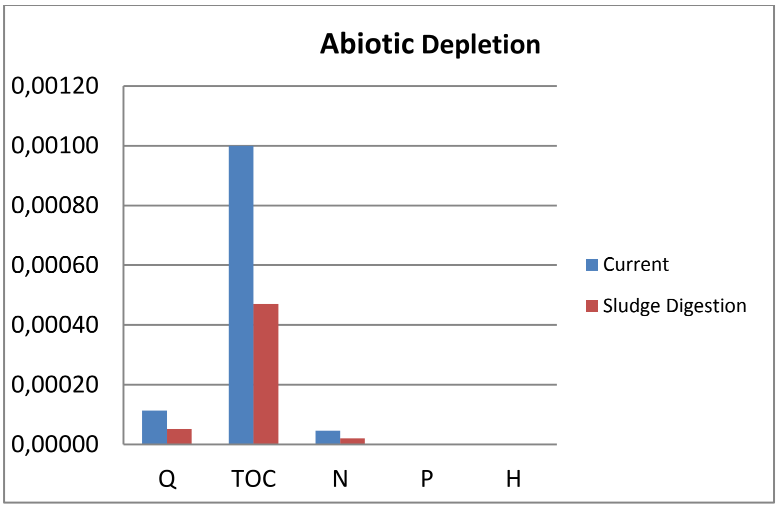

Figure 22. Abiotic depletion category comparison in terms of the 5 main operational values.

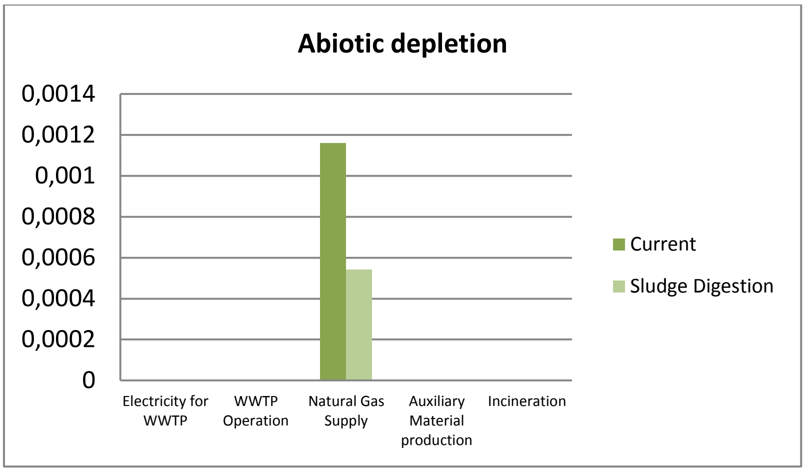

Figure 23. Abiotic depletion category comparison in terms of the processes involved.

6.2.2.2. Global Warming

In the overall results for this impact category (Table 34) the future scenario seems to be at slightly in disadvantage against the current scenario. The main reason for this is the increment in electricity consumption in the sludge treatment stage which almost duplicates with the inclusion of sludge digestion. This increment consequently causes more greenhouse gases to be released to the atmosphere in the electricity supply processes. Additionally, TOC and N concentrations also increase a bit in the inlet of tower biology because the recirculation of highly concentrated supernatant from digested sludge thickening and dewatering; this represents more electricity demand in the Tower Biology and also a high yield in waste air to the atmosphere. The above can be reflected in the "Electricity for WWTP" and "WWTP operation" columns of Figure 25 where the "sludge digestion" scenario shows higher values (around 6% and 0.2% respectively) opposed to the current scenario.

Nevertheless, there are other areas where the current scenario is not favored and therefore counteract the harms above mentioned with respect to the scenario with sludge digestion. This areas are related with the incineration, the auxiliaries production and transportation, and natural gas supply background processes.

Since the sludge production is reduced by 30% with the inclusion of anaerobic digestion, fewer solids are burned and lower greenhouse emissions are generated in the incinerator: As a result the impact value due to the incinerator is diminished by around 26% (Figure 25).

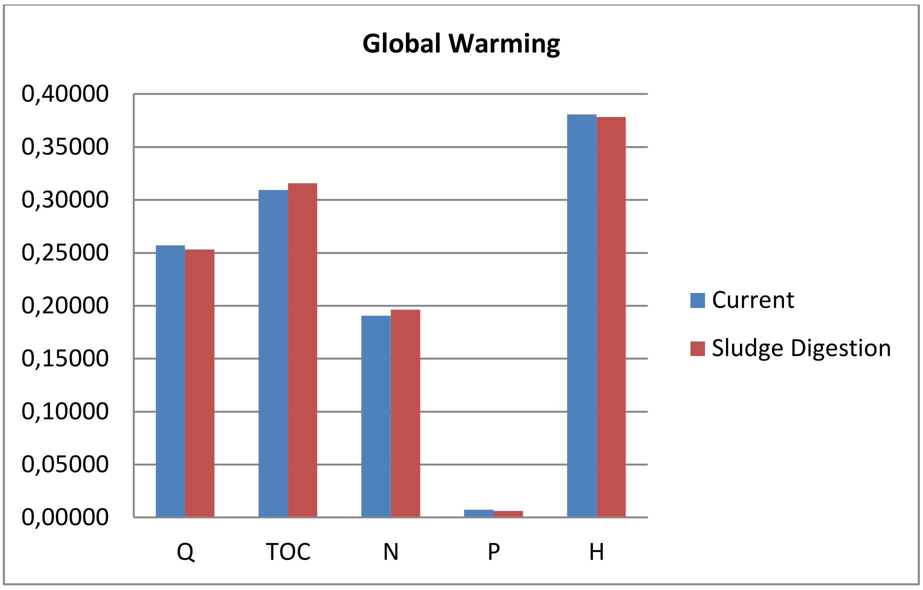

Figure 24. Global Warming category comparison in terms of the 5 main operational values

For the auxiliaries production and transportation background processes, even when a substantial increment of some material is presented (HCl, NaOH and steam), the global warming value decreases about 3% in the future scenario. This is mainly because the lime consumption decreases about 30% in sludge digestion scenario; and as was described section 6.2.1.2, the greenhouse emissions from lime production have a high influence in the overall result.

Natural Gas supply process shows a substantial decrement of more than a 100% in the global warming gas emissions in the new scenario. This due the amount of methane generated in the sludge digestion, which was deducted from natural gas supply volume to quantify the profit in within this scheme. However, despite this decrement the contribution of this process to the impact category overall is just of <1%, then its influence to the total is minimal.

The partitioning of the global warming impact category in terms of the 5 main parameter values can be seen in Figure 24. Here is important to remind that the same inlet and outlet values of these parameters were considered in both evaluated scenarios. The difference between them is just the adjustment in electricity and auxiliaries consumption, and in the sludge and biogas production. Within this context, it can be said that the impact partition in terms of the parameters keeps a proportional distribution in both scenarios, being affected relatively with the increment or decrement of its related process (Figure 25 processes). So the sludge digestion scenario behaves as follows against the current scenario: Hydraulics decreases its impact contribution by 1.64%; TOC increases 2%; nitrogen increases 3%; phosphorous decreases 17%; and Hydrogen decreases 1%.

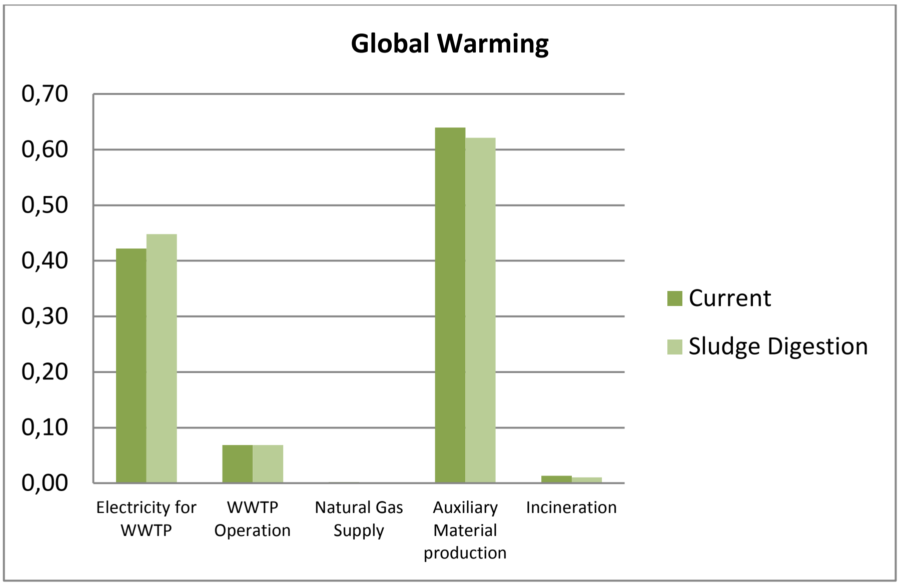

Figure 25. Global Warming category comparison in terms of the processes involved.

6.2.2.3. Acidification

For acidification impact category, the future scenario with sludge digestion seems to have a better environmental profile (Table 34). The detailed analysis in Figure 27 shows that this is due to a decrement in the acidifying emissions (SO_2, NO, NO_x and NH_3) in incineration (26% less), natural gas supply (100% less) and production and transportation processes of auxiliaries (3% less). This decrement is produced because the generated sludge reduction (30% less); the grating credit of the methane; and the lower lime consumption (30% less). Only electricity consumption increment because the inclusion of sludge digestion increases the acidifying value by 6%.

Parameters shares in this category are explained with the acidifying emissions (SO_2, NO, NO_x and NH_3) of the background processes mentioned above whose their supply depend on TOC, Q, N, P or H concentration. Hydraulics decreases its impact contribution by 10%; TOC increases 1%; nitrogen increases <1%; phosphorous decreases 22%; and Hydrogen decreases 1% (Figure 26).

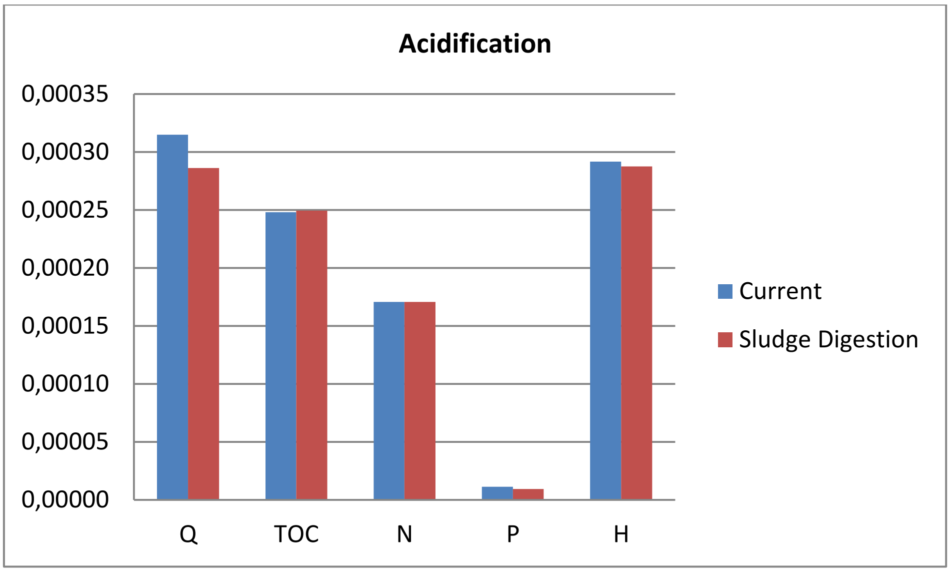

Figure 26. Acidification category comparison in terms of the 5 main operational values.

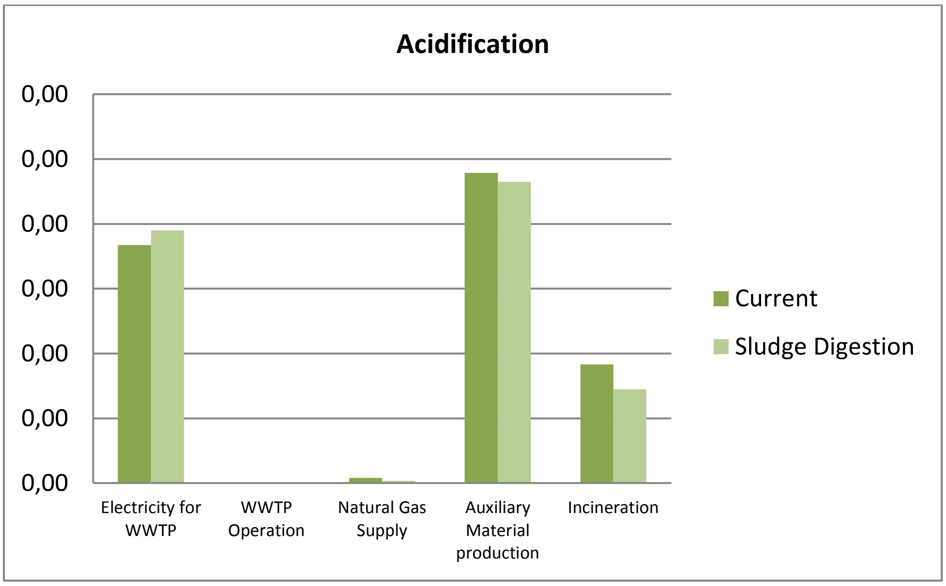

Figure 27. Acidification category comparison in terms of the processes involved.

6.2.2.4. Eutrophication

Eutrophication overall results are similar for both scenarios with a small disadvantage for the current WWTP scheme. This was expected since the discharge operational parameters (COD, N, P) that gives this impact category the main value (WWTP operation in Figure 29) are the same in both cases. Only the slightly differences in the eutrophying emissions (mainly atmospheric deposition of nitrogen gases) of some background processes cause the better performance of the scenario with sludge digestion: Incineration (26% less), natural gas supply (100% less) and production and transportation processes of auxiliaries (3% less). Electricity supply increases its contribution because the already mentioned increment of consumption in the sludge digestion stage (6.2%).

In Figure 28, where eutrophication results in terms of the 5 main operational values is shown, it can be recognized that the impact distribution have a variation in the new scenario for TOC (1% more), Q (16% less), P (<1% less) and H (>100 less). Nitrogen stays the same. Variations, as in the other impacts above described, are due the adjustment in electricity auxiliaries consumption; generated sludge reduction; and biogas production.

In general it can be said that for eutrophication, the elimination ratios in the WWTP treatment scenarios, which have been assumed equal, have a strong influence on the overall result.

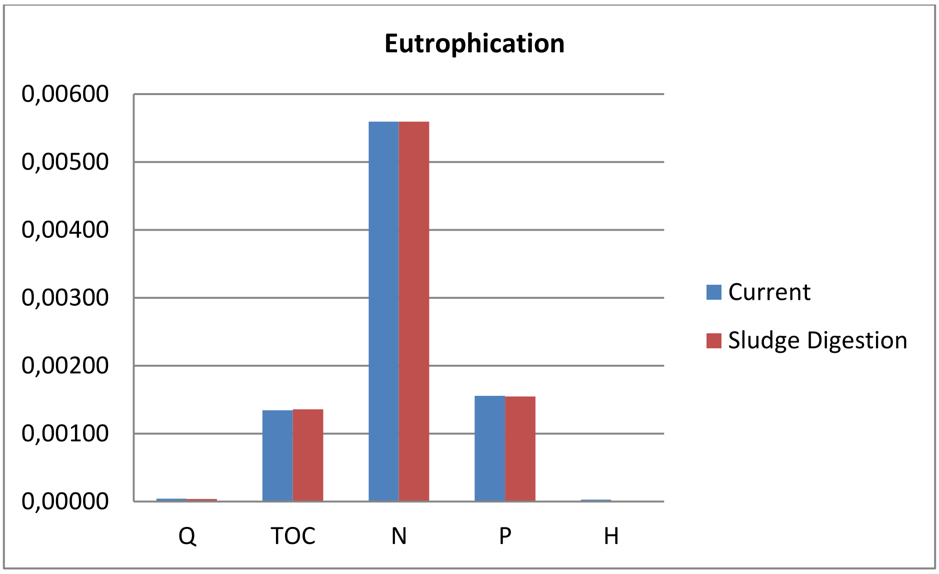

Figure 28. Eutrophication category comparison in terms of the 5 main operational values.

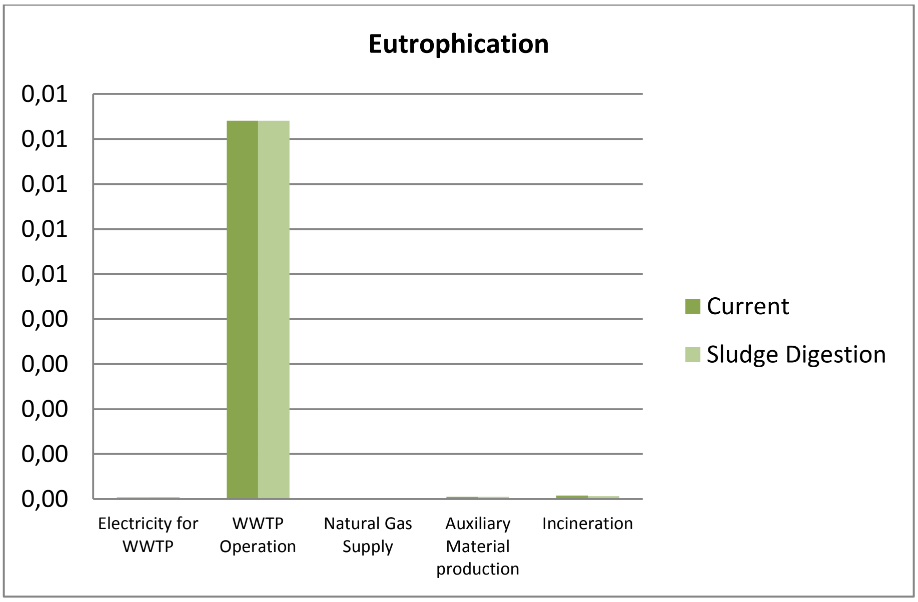

Figure 29. Eutrophication category comparison in terms of the processes involved.

6.2.2.5. Freshwater ecotoxicity

Freshwater ecotoxicity for aquatic and sediment ecosystem have a similar behavior because both are affected by the same toxic substances (heavy metals mainly); therefore the two are included within this section. The overall value of this impact category is better for the current scenario. This demonstrates that energy-related upstream processes (Electricity supply) dominate the ecotoxicological impacts. Figure 31 and Figure 33 show this influence: Around 93% because electricity supply in the sludge digestion scenario, and around 90% in the current scenario.

Minor contribution comes from production and transportation processes of auxiliaries and incineration, but in both cases the toxic substances emitted are less in the sludge digestion scenario. Production and transportation processes of auxiliaries decrease about 3% and incineration about 20% (less sludge burned).

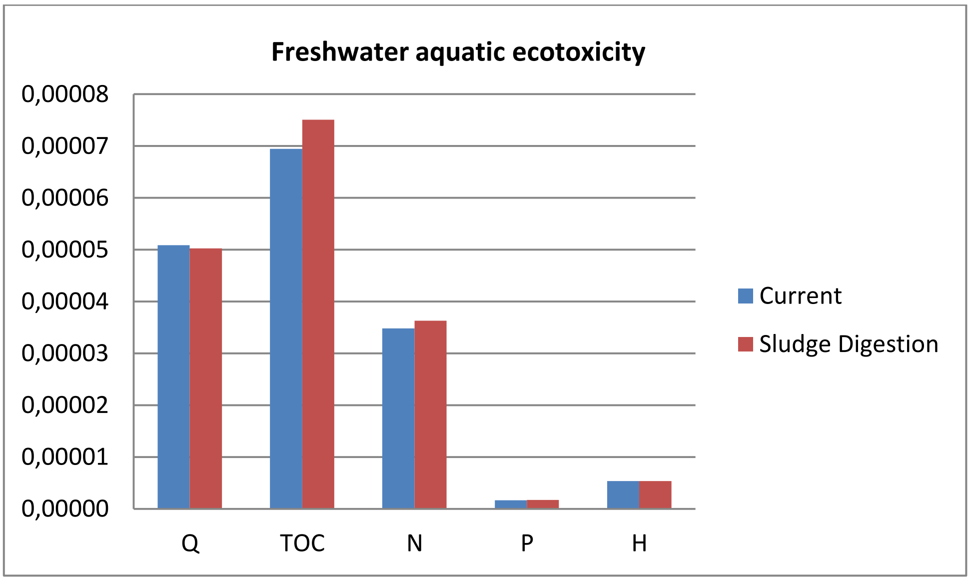

Figure 30. Freshwater aquatic ecotoxicity category comparison in terms of the 5 main operational values

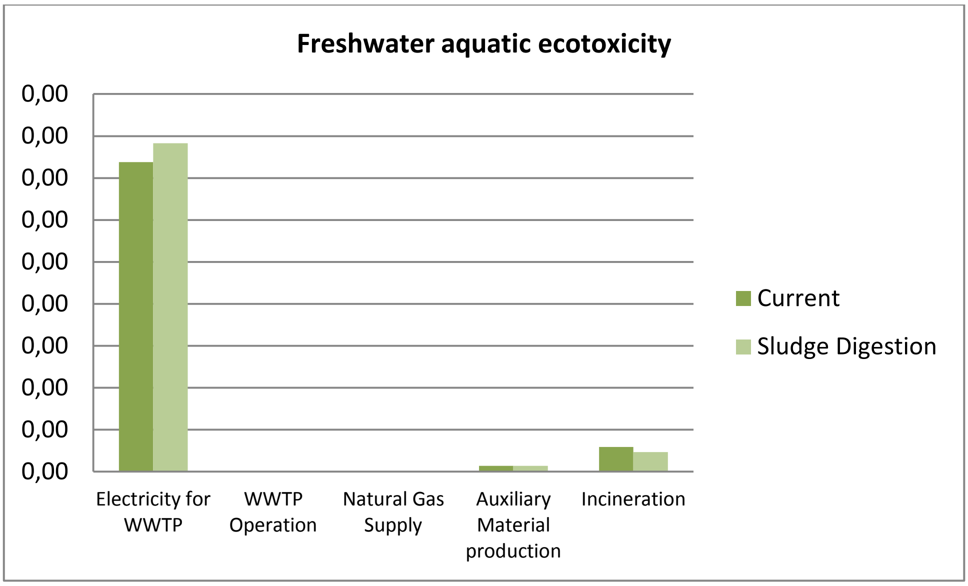

Figure 31. Freshwater aquatic ecotoxicity category comparison in terms of the processes involved.

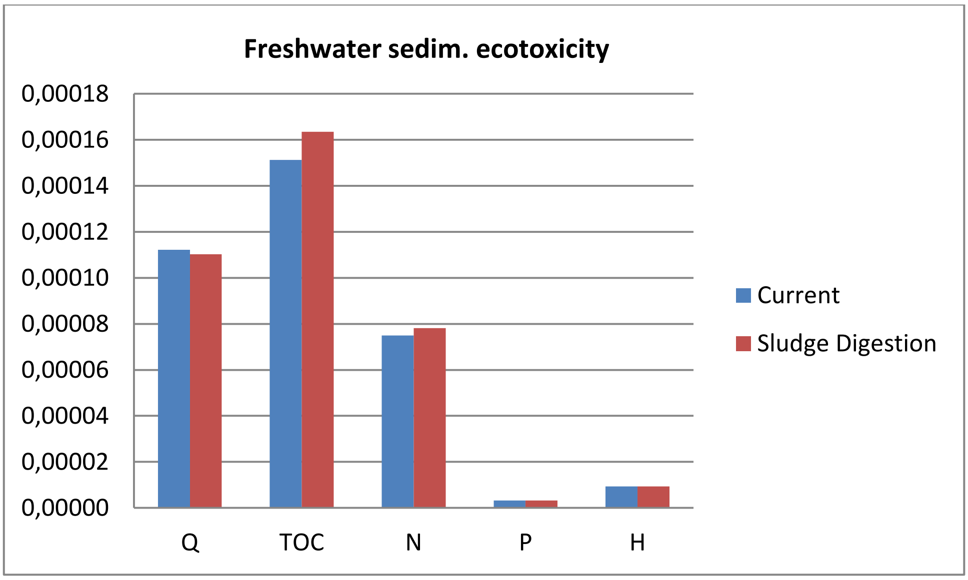

Figure 32. Freshwater sediment ecotoxicity category comparison in terms of the 5 main operational values

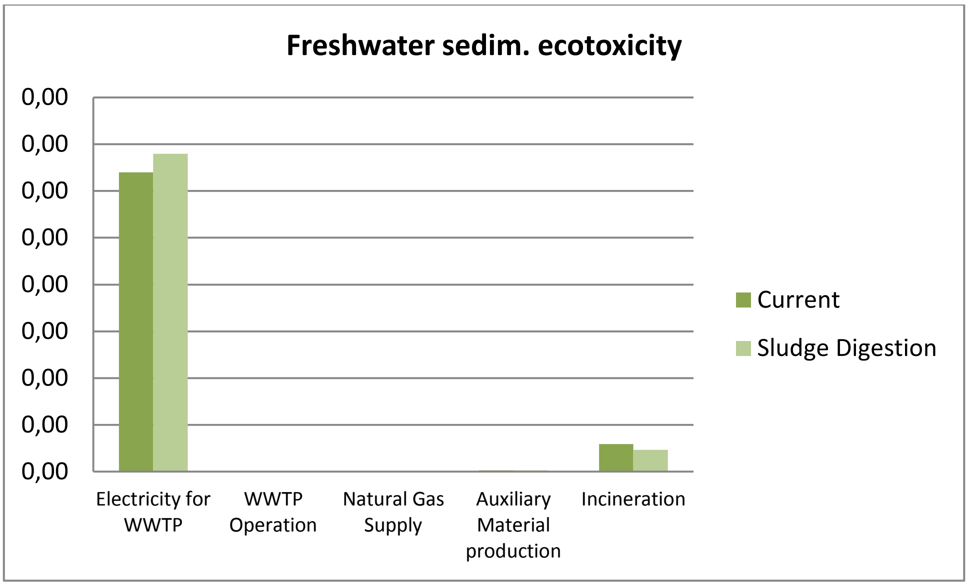

Figure 33. . Freshwater sediment ecotoxicity category comparison in terms of the processes involved.

6.2.2.6. Human toxicity

In general, similarly that ecotoxicity, the major part of human toxicity is caused by the energy supply background processes; consequently the overall result is better for the current scenario. Figure 35 shows this influence: Around 97% because electricity supply in the sludge digestion scenario, and around 96% in the current scenario. Because the dependency of electricity supply processes to the parameters Q, TOC and N, these parameters also proportionally increase by 8%, 2% and 4% respectively.

Production and transportation processes of auxiliaries and incineration demonstrate more favorable results in terms of human toxicity. Production and transportation processes of auxiliaries decrease about 2% and incineration about 26% (less sludge burned).

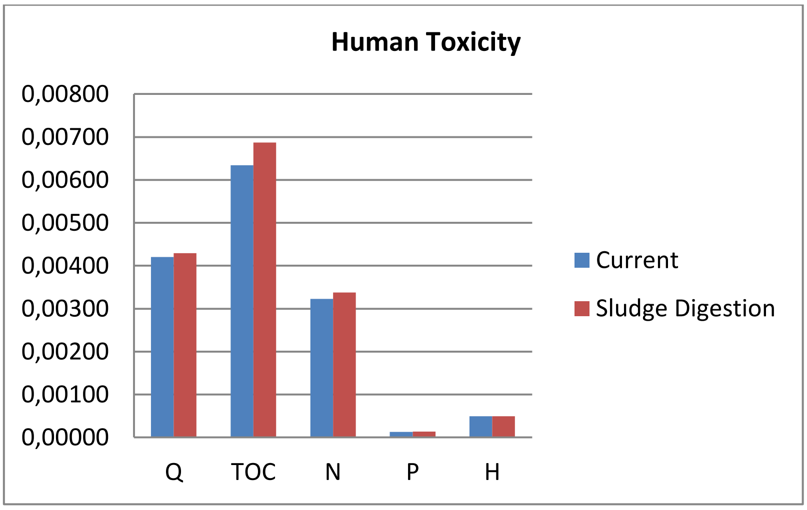

Figure 34. Human Toxicity category comparison in terms of the 5 main operational values

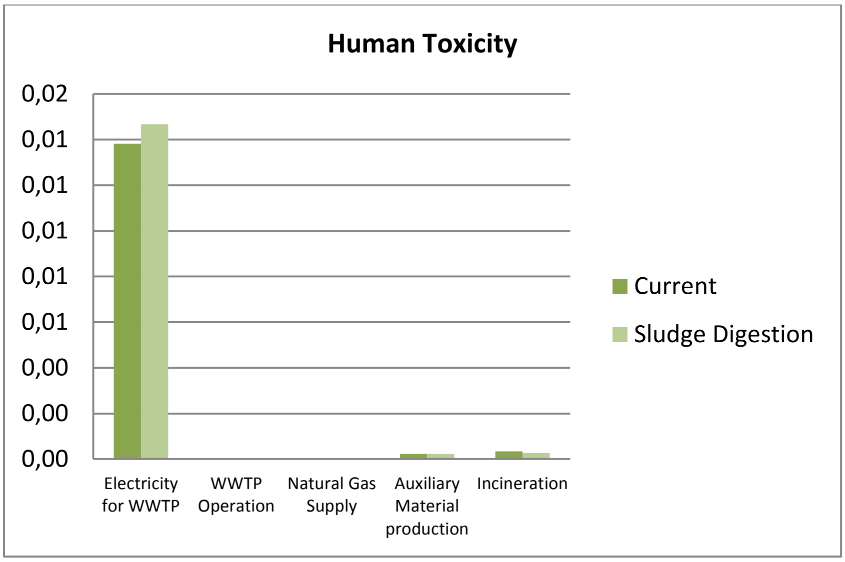

Figure 35. Human toxicity category comparison in terms of the processes involved.

6.2.2.7. Odour

As described in section 6.2.1.7, the process which contributes to this indicator is the Sludge incineration emitting substances to the air like ammonia, acetaldehydes, mercaptans, etc. (Figure 37). One of the main advantages in the sludge digestion scenario is the considerable reduction of biosolids to be disposed in the incinerator, then after the overall result for odour category definitely favors the new scenario since less solids are burnt.

It can be appreciated in Figure 36 that each parameter decreases it causality to the odour category in the sludge digestion scenario by about 30%, which correspond to the percentage of sludge reduction within the new scheme. This since, as described in chapter 5, every kilogram of sludge generated in the system is totally dependent to the inlet value of the main parameters.

In Figure 37 it can be seen how also the decrement of the incineration process contribution to the odour category coincides with the overall sludge generation reduction of 30% that the new scenario offers as benefit.

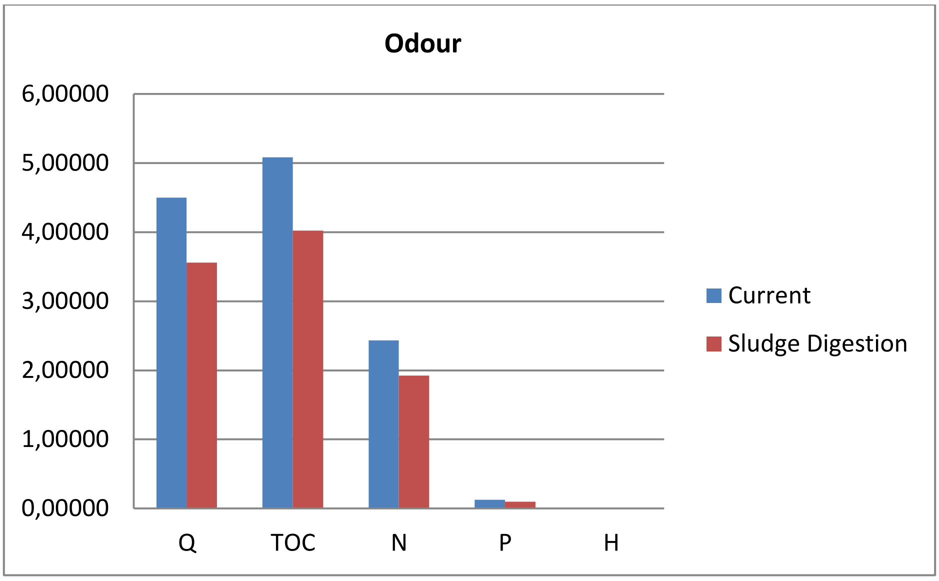

Figure 36. Odour category comparison in terms of the 5 main operational values

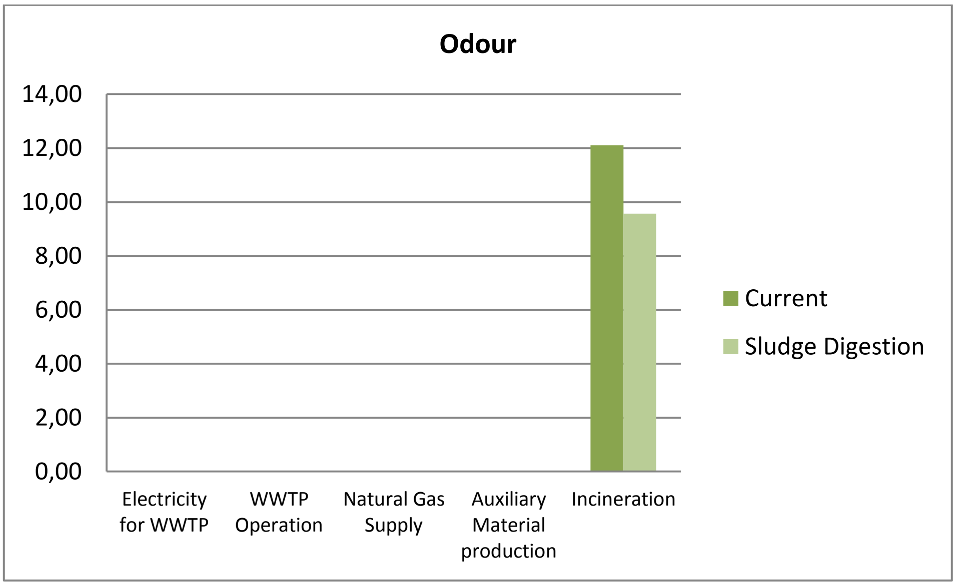

Figure 37. Odour category comparison in terms of the processes involved.

6.2.2.8. Terrestrial ecotoxicity

As terrestrial toxicity is another category for ecotoxicity the results broadly coincide with the freshwater ecotoxicity ones. So it is strongly determined by the transfer of heavy metals to soil emitted by the energy supply processes operation (99%). Figure 39 shows this high influence and how the current scheme has a better performance than the sludge digestion scenario. The incineration has a more optimal impact result in the new scenario (30% less) but its contribution to the total value is minimal (<1%), so it play a negligible role.

Parameters Q, TOC and N also proportionally increase according to its causality to electricity consumption by 9%, 3% and 5% respectively.

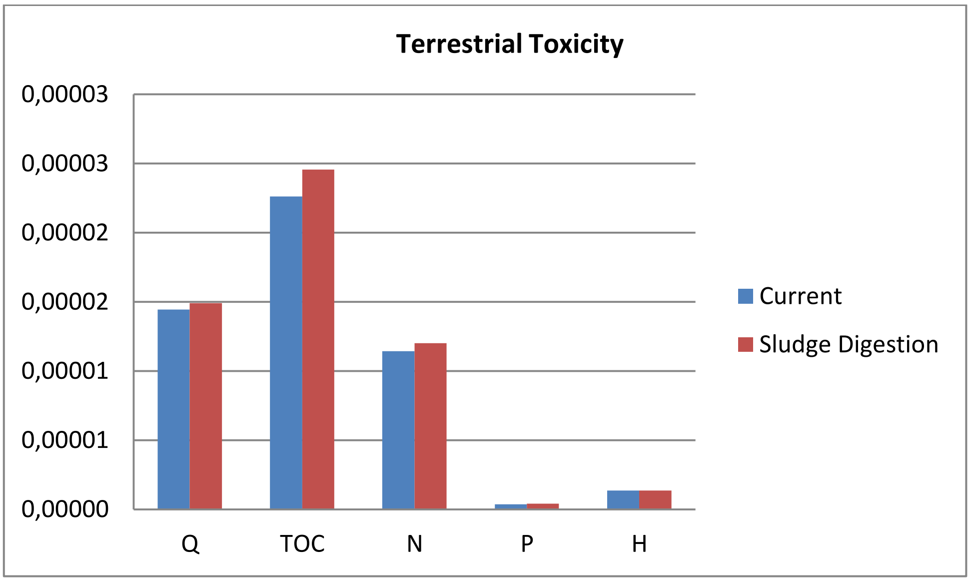

Figure 38. Terrestrial toxicity category comparison in terms of the 5 main operational values.

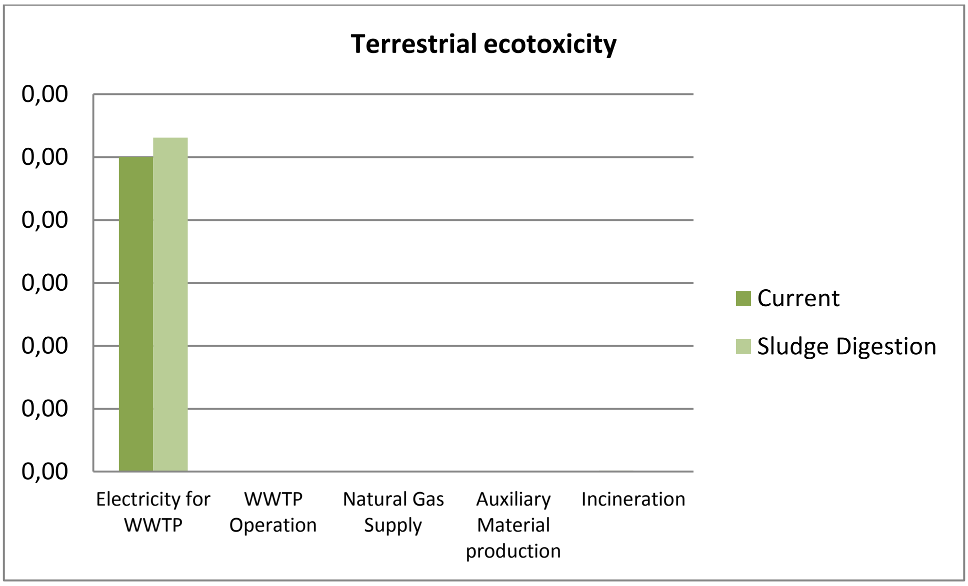

Figure 39. Terrestrial ecotoxicity category comparison in terms of the processes involved.

6.3. Life Cycle Interpretation

The interpretation is the fourth phase in an LCA study and according to the ISO standards the objectives of this stage are to analyze results, explain limitations, reach conclusions and provide recommendations. In last part (section 6.2) the results were already analyzed and discussed, so this section will be limited to a synopsis of the relevant findings and the explanation of the limitations. Conclusions are presented in the next chapter.

In the present LCA the environmental impacts which are the consumption of ancillaries and energy carriers, the generation of sludge, and the emission of pollutants were partitioned to the wastewater composition by their specific cause. There were chosen Hydraulics (Q), Total Organic Carbon (TOC), Total Nitrogen (N), Total Phosphorus (P) and Hydrogen (H+) as main parameters to describe the wastewater composition.

Q TOC N P H

Indicator	Decisive process	Parameter influence	Important emissions or resources	Best performance scenario
ADP	Natural Gas Supply		Raw Natural Gas	Sludge Digestion
GWP	Electricity supply and production of auxiliaries		CO_2 (fossil), N_2O and CH_4	Current
AP	Electricity supply, production of auxiliaries and Incineration		SO_2, NO, NO_x and NH_3	Sludge Digestion
EP	WWTP Operation		N, P and COD	Sludge Digestion
FAETP	Electricity supply		Heavy metals	Current
FSETP	Electricity Supply		Heavy metals	Current
HTP	Electricity Supply		HF, Heavy metals	Current
OD	Incineration		NH_3	Sludge Digestion
TETP	Electricity Supply		Heavy metals	Current

Table 36. Results summary. Abiotic Depletion (ADP); Global Warming (GWP); Acidificaion (AP); Eutrophication (EP); Freshwater aquatic ecotoxicity (FAETP); Freshwater sediment ecotoxicity (FSETP); Human Toxicity (HTP); Odour (OD); Terrestrial toxicity (TETP)

In Table 36 is presented a summary of the relevant findings already discussed in the last section. From this is possible to interpret that for the case of a wastewater system all the environmental burdens are totally dependent on the wastewater parameters which in the present case are the hydraulics plus the composition in terms of the already above mentioned parameters. The variation of any of them would cause an immediate repercussion in all impact categories.

Under this scheme the LCA has been completed beneath two scenarios: The first one was Currenta system under the actual operation conditions (2010 data). The second scenario was the Currenta system with the inclusion of sludge digestion in the solids treatment stage. The impact assessment showed that the second scenario (sludge digestion) promises slightly environmental improvement potentials in the overall in terms of pe*a (Normalized result in Table 34). This improvement is produced because the advantages that sludge digestion offers: The sludge generation reduction which signify less solids to be disposed (30% less); the grating credit of the produced methane which allow to get a revenue from the solids treatment; and the lower consumption of some significant auxiliaries like lime (30% less). Nevertheless, impact categories global warming, Freshwater ecotoxicity, Human Toxicity and Terrestrial toxicity resulted marginally better in the first scenario (current); this mainly because electricity consumption increment (duplicates in sludge treatment stage) due to extra sub processes that the sludge digestion requires.

Additionally, to complement the comparison done above (in terms of the normalized results), a contrasting analysis using a T diagram was done (Figure 40). In this diagram relative scores with the same priority can be counterbalanced against each other. The ranking of each impact (high, medium or high) was done using Remy´s ranking method (Remy, 2010), where based on the ecological hazard, distance to the target, and specific contribution of each impact, a priority is assigned.

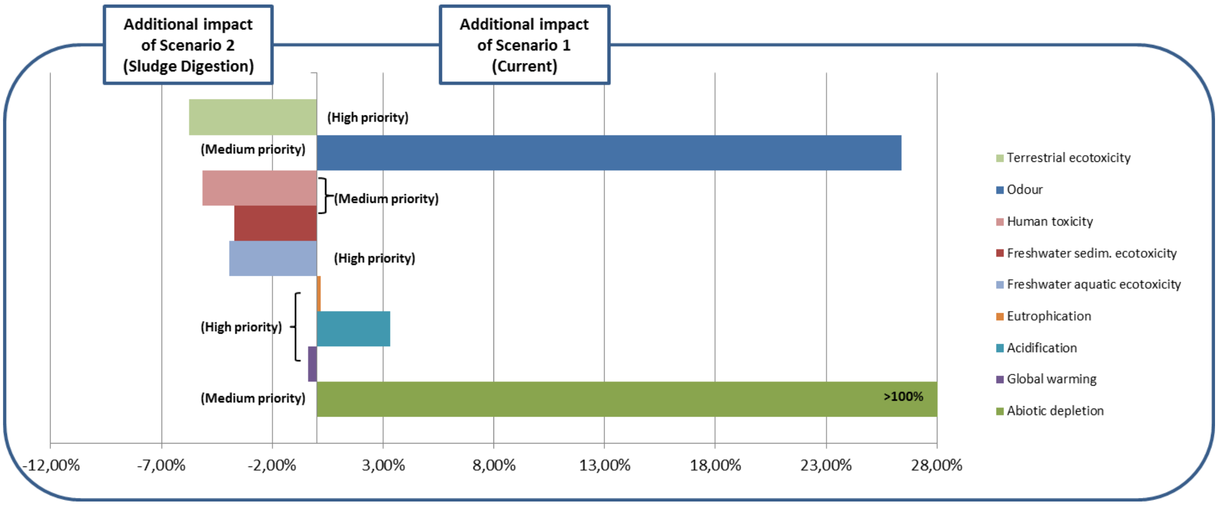

Figure 40. T-diagram for the two scenarios comparison

In Figure 40, the orientation of the bars in the diagram shows which of the investigation scenarios analyzed exhibit higher indicator results in which impact category, i.e. which of the two systems is more likely to create environmental pollution in its category. The lengths of the bars represent the additional burden attributable to each system (in percent). In the left side are shown the additional impacts of sludge digestion scenario and in the right side of the diagram are shown the additional impacts of the current scenario. Just beside each impact bar in brackets, is exhibited each impact priority based on ecological hazard, distance to target and specific contribution. Within this context, for the present study it can be said that the sludge digestion scenario has benefits in abiotic depletion and odour (medium) and eutrophication and acidification (high). Still in global warming and ecotoxicities considerable impact is attributable to the sludge digestion scenario. Then after, the result of this comparison can be declared as slightly favorable to the second scenario.

Some limitations are present in the current study. These limitations can put certain degree of uncertainty in the results. As last part of the interpretation the main considered limitations of the study are listed below:

- The limitations of using the CML methodology: All the impact category results are calculated from the substance and resources list defined by this methodology. Consequently it is a limitation that substances or resources not characterized in this list are not considered within the environmental impacts. For this specific study the principal example of this limitation is that water use (water abstraction from a natural sources) is not included in the method; so all the possible environmental impacts coming from the usage of this resource are being omitted.

- Life Cycle Inventory limitation: In order to simplify the life cycle inventory and according to the study scope, all the information gathered was related with the parameters TOC, N, P and H; still, information about other parameters like AOXs and heavy metals, which give an important value to ecotoxicity impacts, were no considered. Additionally for simplification purposes, all the data in terms of TOC, N and P was collected as total, being that they are a mixture of various species. For the specific case of TOC it is also a limitation with respect to ecotoxicity since this parameter includes unidentified organic pollutants and remaining quantities of known organic pollutants, which are not separately measured, but hidden in the organic bulk matrix; then after only quantified in eutrophication.

- Linearity: The present LCA consider all processes as linear, i.e. doubling the consumption of material is assumed to have double impact, and the same applies for doubling the release of a pollutant to the environment.

- Databases dependency: As mentioned in chapter 5, for calculation of inventories of background processes were used modules from datasets provided within Umberto software. This is an advantage because it is possible to consider more related processes in the assessment. Nevertheless, it is also a limitation since some of the pre-defined modules differ considerably from the real process and then after lead to uncertainty in the results.

Briefly, according to the limitations above described, it can be said that the present Life Cycle Assessment is not a high precise evaluation of the environmental performance of Currenta's WWTP. Still it offer both perspective and prospective plant analysis that allow to rate in environmental terms the system; and furthermore, make impact comparisons when any process modification are intended to be made. Anyways, by detailing the Life Cycle inventory and particularizing backgrounds processes, higher precision can be achieved.

CHAPTER 7. CONCLUSIONS

From the present study, conclusions can be drawn from two different points of view: First from the methodological perspective, i.e. relevant finding about the procedure of applying and adapting the Life Cycle Assessment scheme to the WWTP under study; and secondly specifically about the evaluation results which yield as a result Currenta WWTP actual environmental status and a contrasting comparison with an intended future scenario that include sludge digestion in the process.

Methodologically speaking, the structure followed was based on previous research in the area and in accordance to the structure of ISO 14040/44 standards. The peculiarity of the present study lies in the fact that the system analyzed resembles a multi-input/output scheme and then, special attention was required in design an allocation model to define the Life Cycle Inventory (LCI). The multi-input/output allocation developed within the present work offers the possibility to design wastewater specific inventory data within the context of LCA. With the inclusion of the parameter dependent consumption factors it can be identified the real partitioning of each of the auxiliaries according to the influent composition variation. In this manner, they can be analyzed “what if” inlet characteristics scenarios where immediate repercussion in the auxiliary consumption and therefore in the environmental load, can be appreciated. In Table 20 chapter 5 within the current work, are given the relative percentages of the estimated consumption factors for each ancillary needed in the WWTP according to the allocation criteria described in this same chapter.

Additionally, transfer coefficients express the fate of inlet substances described by the selected parameters within the environmental compartments. In Table 26 of section 2.1.5.2 are indicated the transfer coefficients for the emission to air, emission to water, and sludge to incinerator plant considering the entire wastewater treatment system. With these values was possible to make an overall idea of the environmental impact of each parameter, and the WWTP removal efficiency.

As mentioned before in the interpretation, it was assumed that the relationship between parameter element and consumption is linear. This assumption is state of art in LCA multi input-output modeling and is only valid as long as emissions are under the allowed legal limits. For further applications the present model will be only accurate if the wastewater composition parameters do not vary significantly from the average wastewater composition the model was designed.

Also it must be mentioned the uncertainty of the model. The allocation criteria considered involves the setting of some factors and contemplation of some assumptions that can be recognized arbitrary and therefore speculative. It is difficult to define general rules for environmental load allocation because of the variety of options; sometimes even different criteria can be used for the same case. This degree of arbitrariness has been widely recognized. Despite this uncertainty, this kind of modeling contributes in achieving more detailed WWTP process description that allow identification of hotspots regarding environmental impacts. This later on can become a great tool to define priorities for process optimization.

The obtained Life Cycle Inventory (LCI) results formed the basis for the Life Cycle Impact Assessment. To achieve that, first LCI results were linked to their corresponding background inventories. Then, the cumulative results were assessed with CML (Center for Environmental Science, University of Leiden) impact assessment method using Umberto software.

A rough energy analysis for the construction phase was done to make an approximated comparison against the foreground system (operational stage). The analysis was highly dominated by the operational stage (94-6%). This coincided with numerous related studies where it has been demonstrated that the impact in the construction phase is much lower than the operation.

One of the goals of the study was to generate information on the environmental life cycle of the CURRENTA wastewater treatment process advancing in the existing approaches of LCA methodology. In this sense, the environmental profile provided in section 6.2.1 fulfills this goal. In this profile is possible to appreciate the contribution in terms of the dependence of each impact category to the main parameters considered. The environmental profile was normalized in relation to the latest total available emission data for Germany, so the resulting normalized unit was then person equivalents*year in this country. According to this result the specific contribution of all indicators in terms of the total for the present study were very low, all under 1% of the entire emission reported in Germany. Eutrophication was the highest with a normalized value of 0.13%. This was expected since this category describes mainly COD, and nutrients released to the environment, which are the main elements that are intended to be removed within the treatment. These elements are highly concentrated in the inlet of the process and even when they are reduced considerably, the removal is not of 100%. Hence it can be said that Currenta WWTP has an insignificant share of the total impact categories demand in Germany.

A disaggregation of each indicator in regards to the processes involved was done to better understand this resulting environmental profile. From this it can be recognized that electricity generation is one of the dominant overall processes for the high priority impact categories global warming and ecotoxicitiy. In causative terms of WWTP sub processes, the Tower Biology sub stage resulted to be the most demanding user with 55% of the total energy consumption from which 57% was dependent of the TOC concentration, 32% of the N, 12% of Q and <1% because P. For that reason, it is important to focus on increasing the energy efficiency of the wastewater work in order to increase its overall environmental performance.

Production and transportation of auxiliaries were identified as important contributors for global warming and acidification, which are two high priority impact categories. Therefore, find a way to optimize its usage becomes important. The most influential auxiliary proved to be the lime, which is consumed in 74% by the pretreatment sub stage. Here its usage depends in a 75% on the H^+ ions concentration. Other auxiliaries seem to have a marginal contribution; nonetheless their process consideration using Umberto database was not specific.

Natural Gas supply had a decisive contribution for Abiotic Depletion, which is a medium priority impact category. Natural gas consumption most demanding sub stage was the waste air treatment, and the volume needed there relies on 96% of the TOC concentration in the inflow of the tower biology.

The incineration had a discrete but constant contribution of <20% in high priority impact categories. For this process has to be noted that was necessary to adapt an already predefined module for sludge incineration. This consideration deviated slightly the real result since there were very particular characteristics of Currenta incineration, like sludge properties and incinerator operation, that were not evaluated as they really are.

Regarding the comparison of the two considered scenarios, the one which include sludge digestion slightly improved the environmental performance when contrasting the results. Detailed analysis using T-diagram showed that the sludge digestion scenario had benefits in the medium priority impacts abiotic depletion and odour; and in the high priority impacts eutrophication and acidification. These benefits were due the sludge generation reduction of 30%, which would signify fewer solids to be disposed; the grating credit of the produced methane which would allow getting revenue from the solids treatment; and the lower consumption of some significant auxiliaries like lime, which would decrease its usage about 30%. Still in global warming and ecotoxicities considerable impact was attributable to the sludge digestion scenario and represented a drawback to the proposal. This mainly because electricity consumption increment, which would duplicate in sludge treatment stage, due to extra sub processes that the sludge digestion would require.

It must be emphasized that the compiled LCI database and associated LCIA for the present study are specific for Currenta WWTP; and that their intended audience is conformed of industry-internal personal. Therefore, the LCA study results cannot be generalized for any other treatment facility. Still, LCA practitioners are expected to consider this study for methodology comparison intentions.

In general LCA approach resulted to be valuable for assessment of the environmental impact of Currenta WWTP. It allowed to identify system hotspots that later can be used by the company experts to define priorities for process optimization; and for the case of the comparison with sludge digestion future scenario, was useful to appreciate the benefits and drawbacks in environmental impacts terms. However, it must always be recognized that LCA studies will not solve the environmental problems that face a company, but will give the right direction to define where the efforts need to be focused.

For further research, and to completely set LCA tool as fix methodology in CURRENTA wastewater facility for additional ecological evaluations, it is strongly recommended to increase level of detail of the analysis. This mainly by returning to the Life Cycle Inventory of the study and trying to completely eliminate the simplifications considered. This would be the inclusion of all possible data regarding pollution emissions (heavy metals, AOXs, diverse compounds species) and its linkage to the main parameters (Q, TOC, N, P and H). Additionally is important for the case of the incineration to characterize the process with the real Currenta conditions; this would imply another complete LCA for the incinerator, but becomes necessary to decrease uncertainty in the environmental impact results.

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