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1. INTRODUCTION

1.1. Background

Human manipulation of the environment and specially the non-sustainable exploitation of natural resources have led to the equilibrium breaking of different natural ecosystems, which affects the soil, water and atmosphere environments. Focusing on water resources, human activity has directly and indirectly altered the quality of fresh-water, and in some areas reduced the quantity of these resources. Wastewater can be defined as the flow of used water discharged from homes, businesses, industries, commercial activities and institutions, which is directed to treatment plants by a carefully designed and engineered network of pipes. The term “domestic wastewater” refers to flows discharged principally from residential sources generated by such activities as food preparation, laundry, cleaning and personal hygiene. It is important that the wastewater is properly treated before discharging to the environment (rivers, lakes, sea). Pollution caused by untreated water can have a damaging ecological impact that can be harmful for fishes and aquatic plants. The overall water management objectives for wastewater treatment are associated with the removal of pollutants and the protection and preservation of our natural water resources, such as rivers.

The traditional way to treat domestic wastewater is by applying activated sludge processes. These, are biological processes by which the activity of microorganisms under controlled operating conditions permits the biodegradation of organic matter and nutrients (nitrogen and phosphorous) from wastewater. Wastewater treatment plant (WWTP) facilities are designed and constructed to conduct these processes in a efficient way. There are several guidelines to design WWTPs available (e.g. Metcalf & Eddy, ATV, Grady, Ten State Standards and HAS principles). However, there are different sources of uncertainty in these protocols, which can result to oversized designs (leading to higher operating and construction costs) or undersized designs (leading to lower effluent quality or limiting future capacity of the plant). In order to manage with uncertainty associated to the design of WWTPs, governments and companies worldwide are investing in research, with the objective to improve their designs.

In this sense, the goal of the IWA Task Group on Design and Operations Uncertainty (DOUTGroup) is to critically summarize the work that has already been done on the topic of uncertainty evaluation and to identify gaps in the available methods or knowledge used for WWTP design. The DOUTGroup intends to bring together the collective knowledge of engineers, academics and plant owners, from several countries and continents. The IWA task group is the first phase of a multi stage project that will culminate the development of an industry-wide, recognized protocol that incorporates uncertainty evaluations in model-based plant design and optimization. The protocol will incorporate transparent and objective methods for estimating new design safety factors that can be widely used by the engineering community. Part of the work from the DOUTGroup is coordinated by Marc Neuman and Prof Peter Vanrolleghem working at model*EAU* research team which is built around the Canada Research Chair on Water Quality Modelling, at the Laval University of Quebec (Canada). The research themes of model*EAU* are built around the development and use of quantitative, model-based methodologies to support decision-making that considers the receiving water quality as an important criterion. model*EAU* has long-term collaboration with the *Catalan Institute for Water Research* (ICRA) located in Girona (Spain), where research is conducted about all the aspects that involve the water, specially the rational use and the effects of the human activity on the water resources.

This thesis is framed within the research conducted in the DOUTGroup and is the result of the collaboration between model*EAU* and ICRA. Thanks to the PROMETEU program of the *Univesitat de Girona* and *Becas Bancaja*, a stage of six months at model*EAU* was conducted during the first semester of the 2010/2011 season. The work at model*EAU* was directly supervised by Marc Neumann (model*EAU* postdoctoral researcher) and the work at ICRA by Lluís Corominas (postdoctoral researcher), who are the supervisors of the thesis. Also, there has been significant contribution of Prof Peter Vanrolleghem (head of model*EAU*, Canada) and Xavier Flores-Alsina (Junior researcher at Lund University, Sweden).

1.2. Objectives

The main objective of this project is to contribute to the understanding of WWTP design methodologies and therefore help engineers to improve their WWTP designs. More specifically, the objective is to analyse and compare multiple WWTP design guidelines. The sub-objectives are:

- A) To deepen the knowledge of the two selected guidelines: Metcalf & Eddy and Grady. This objective includes three levels:
- 1) *Qualitative analysis*: It is the first analysis level and consists in the study and understanding of the approach, procedure, and equations used in the design guidelines
- 2) *Quantitative analysis*: The objective of this analysis is the study of the design results for a specific case (single scenario)
- 3) *Stochastic analysis*: Analysis of the design results for multiple cases using Monte- Carlo (MC) simulations in *single* and *multiple scenarios*
- B) To contribute to the development of an automatic tool to allow for simultaneous analysis and comparison of multiple WWTP designs obtained from different guidelines.
- C) To conduct an analysis and comparison of these designs through the methodology defined by using of the tool developed.

1.3. Specifications and scope

To achieve the objectives proposed, it is necessary to carry out the following tasks, which are conducted at different institutions (ICRA and model*EAU*). The starting point of this project was in ICRA (Parc Tecnològic, Girona), during the month of july of 2010, defining the objective of the project and starting the literature review. Afterwards, the work was continued at model*EAU* (thanks to the PROMETEU program) for 6 months and finally, the work is finalized at ICRA.

The focus of this project is the analysis and comparison of two widely recognized design guidelines used by the engineers for WWTP design: i) Metcalf & Eddy and ii) Grady guidelines. The WWTP configuration selected in the case study is the Modified Ludzack Ettinger (MLE) used for the removal of nitrogen and organic matter coming from domestic wastewater. The tasks related to the three objectives defined in section 1.2. are:

A) Objective 1: Deepen the knowledge of the two selected guidelines (Metcalf & Eddy and Grady).

- Acquire knowledge about wastewater treatment, WWTP design, activated sludge process, and MLE configuration.
- Qualitative analysis of the design guidelines.

B) Objective 2: Contribute to the development of an automatic tool to allow simultaneous analysis and comparison of multiple WWTP designs.

- Familiarization with WWTP modelling, the Monte-Carlo method and the Matlab software.
- Verification of the Metcalf&Eddy code previously developed at model*EAU*.
- Coding of Grady design guideline in Matlab.
- Development of a methodology to analyze and compare simultaneously multiple design guidelines: Adaptation of the Monte-Carlo algorithm for the simultaneous calculation Metcalf&Eddy and Grady design guidelines.

C) Objective 3: Conduct an analysis and comparison of these designs through the methodology defined by the using of the tool developed.

- Definition of scenarios
- Simulations of the scenarios using the automatic tool developed.
- Interpretation of the results.

2. METHODS

This section gives a general overview of the methodology used in this project for simultaneous analysis and comparison of multiple WWTP design guidelines. The next sections provide: i) a brief description of WWTP design methodology, ii) the configuration of the process and plant setup, iii) a description of the software tool developed for the simultaneous analysis and comparison of multiple design guidelines, and finally iv) the methodology used in the analysis and comparison of design guidelines. As mentioned before, in the case study the widely recognized Metcalf&Eddy and Grady design guidelines are selected to design the modified Ludzack-Ettinger (MLE) configuration of the activated sludge process.

2.1. Description of WWTP design general methodology

The widely-accepted methodology used for designing WWTPs is presented in **Figure 1.** First, the design initial assumptions are defined, i.e. influent fractions, safety factors, operational conditions, and effluent requirements. These assumptions are choices made by the different stakeholders involved in the design process (i.e. design engineer, operator, regulator, and plant owner). Then, these initial assumptions are applied to a set of equations, rules or expert knowledge (normally based on design guidelines) and the design variables are obtained for that particular case (i.e. reactor volumes, air demand or recycle flow-rate).

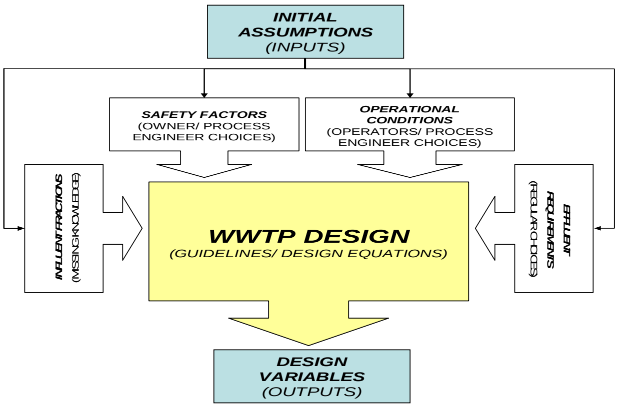


Figure 1. Design methodology for WWTP selected, observing the initial assumptions (influent fractions, safety factors, operational conditions, and effluent requirements) assumed as inputs, and the design variables obtained (outputs) by the propagation of the initial assumptions in design equation.

2.2. Configuration of the Process and Plant Setup

The objective of this section is to present the process configuration and the inputs of the plant setup used in the case study to design the modified Ludzack-Ettinger (MLE) configuration.

2.2.1. Modified Ludzack-Ettinger (MLE) configuration

The purpose of the modified Ludzack-Ettinger (MLE) configuration is the removal of nitrogen reduced to nitrogen gas (N_2). In base to that, the process configuration consists an aerobic and anoxic process, where the removal of nitrogen is carry out in two steps by the nitrification (aerobic zone) and denitrification (anoxic zone) reactions. The **Figure 2** shows a schematic diagram of the process reaction for the removal of nitrogen.

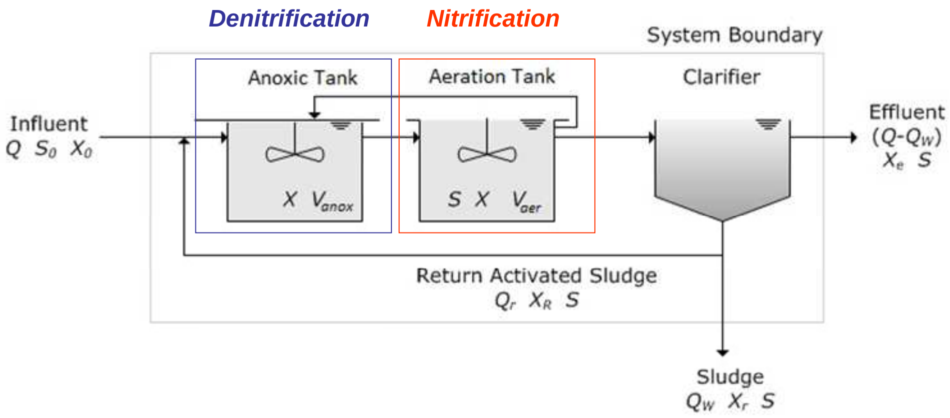


Figure 2. Schematic diagram of the MLE configuration (nitrification and denitrification) for the removal of nitrogen.

The MLE configuration is an activated sludge process configuration, which includes aerobic and anoxic zones to provide controlled conditions to remove organic matter and nitrogen from domestic wastewater (see **Figure 3**). Nitrogen removal processes incorporate aerobic zones (AER) for *nitrification* (biological process conducted by autotrophic microorganisms that obtain energy from the oxidation of ammonia into nitrate) and anoxic zones (ANOX) for *denitrification* (biological process conducted by heterotrophic organisms that convert nitrate to nitrogen gas by using organic matter as electron donor in the absence of oxygen). As denitrification requires a source of organic matter, the MLE configuration places the anoxic zone at the beginning (where organic matter is available from the wastewater) and the aerobic zone afterwards (see **Figure 3**). With this configuration a mixed liquor recirculation (Q_{INT}) to transfer the nitrate-N generated in the aerobic zone back to the initial anoxic zone is required.

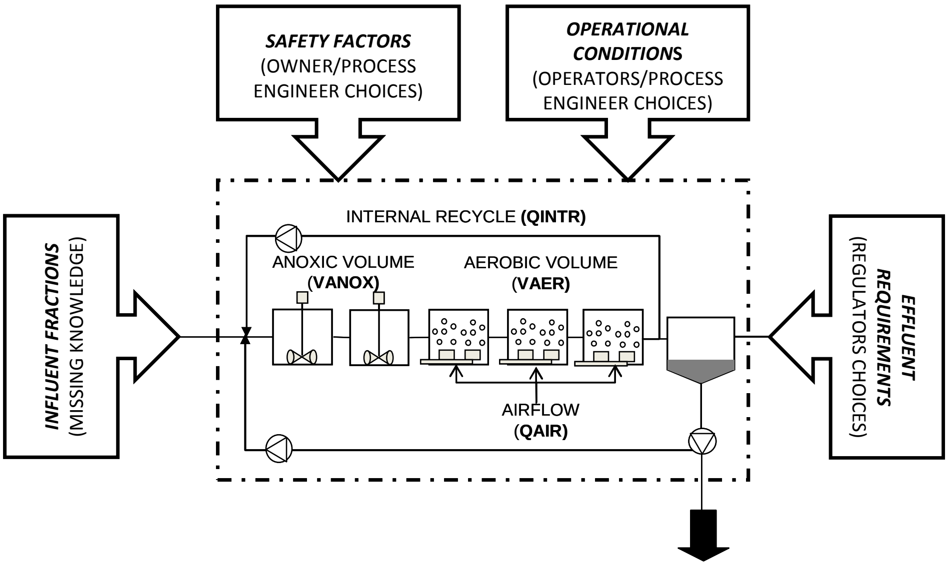


Figure 3. Sources of uncertainty (influent fractions) and stakeholder choices (safety factors, operational conditions, effluent requirements) that determine the final activated sludge plant design.

2.2.2. Definition of the case-study

A case-study is defined for this project, based on the principles of the Benchmark Simulation Model No 1 (BSM1) (Copp, 2002). The WWTP that will be designed according to different guidelines is a WWTP that has to treat wastewater from 100 000 population equivalents. The composition (taken from Copp, 2002) corresponds to typical municipal wastewater, referenced as *Dry Influent* in m-file of this work. A summary of the influent characteristics of BSM1 model is presented in **Table 1**.

Furthermore, the studied guidelines use kinetic and stoichiometric parameters for the reactions that take place in the aerobic and anoxic reactors. The values for this case-study used in each design guideline for all the analysis levels are the same default values as in the Activated Sludge Model No 1 (ASM1) defined by IWA (see **Table 2**). The rest of the parameters plant setup, i.e. safety factors, operational conditions, and effluent requirements, will be selected in base to the criteria of analysis and comparison of the guidelines, in the definition of the scenarios. In this case study, the design variables are represented by *[X]* and include V_{AER}, V_{ANOX}, Q_{INTR} and Q_{AIR}. To obtain the design variables *[X]*, the non-linear implicit algebraic equations of the Metcalf&Eddy and Grady guidelines are implemented as m-file in Matlab.

Table 1. Summary of the influent characteristics defined by the BSM1 (Copp 2002).

Summary Influent Characteristics (BSM1, Copp 2002)		
Characteristics	**Units**	**Values**
Q	m^3/d	18.336
BOD_5	mg/l as COD	174,8
COD_{TO}	mg/l as COD	360
TKN	mg/l as N	51,47
TSS	mg/l as TSS	176,88

Table 2. Stoichiometric and kinetic parameter values in COD/TSS Units from Activated Sludge Model No 1 (ASM1) defined by IWA.

Stoichiometric and Kinetic Parameters Values			
Parameter		**Units**	**Value at 20ºC**
Heterotrophic bacteria		**Coefficients**	
	$\mu_{OHO,Max}$	g TSS·(g TSS·d)$^{-1}$	6
	$K_{SB,OHO}$	g COD/m^3	20
	Y_{OHO}	g COD/g COD	0,67
	b_{OHO}	g TSS·(g TSS·d)$^{-1}$	0,24
	$f_{XU\_OHO,lys}$	mg debris COD/mg biomass COD	0,21
		Temperature correction factors	
	$\mu_{OHO,Max}$	-	1,072
	b_{OHO}	-	1,12
	$K_{SB,OHO}$	-	1
Autotrophic bacteria		**Coefficients**	
	$\mu_{ANO,Max}$	g TSS/g TSS·d	0,8
	$K_{NHx,ANO}$	g NH_4-N/m^3	1
	Y_{ANO}	g COD/g NH_4-N	0,24
	$K_{O2,ANO}$	g/m^3	0,4
	b_{ANO}	g TSS/·(g TSS·d)$^{-1}$	0,15
		Temperature correction factors	
	$\mu_{ANO,Max}$	-	1,103
	$K_{NHx,ANO}$	-	1
	b_{ANO}	-	1,12

2.3. Software Tool Developed to Analyze and Compare Multiple Design Guidelines

2.3.1. Tool Configuration

This section presents the structure of the software tool developed for the simultaneous analysis and comparison of multiple design guidelines (see **Figure 4**). As mentioned before, the objective of the tool is to facilitate interpretation of design guidelines. Thus, the tool is designed to conduct single or multiple design exercises in an automatic way, exploring ranges of initial assumptions required for the designs. The usefulness of the tool is illustrated by the comparison of two design guidelines.

In the quantitative analysis (single simulation), the design guidelines are analyzed and compared in a deterministic case (one sample), using the initial default values defined in the tool setup. In the stochastic analysis (multiple simulations) the methodology proposed for the tool is based on Monte-Carlo (MC) simulation, with the main idea to map the initial assumptions into probability distribution functions: i) the uncertainty of the influent wastewater fractionation, ii) the possible effluent requirements considered by the local regulators, iii) the operator preferences and iv) the degree of safety that the plant owner feels comfortable with. The Latin Hypercube sampling (LHS) technique is applied to generate values using uniform probability distributions from the input ranges for these four categories (initial assumptions). Then the initial assumptions are propagated to the design equations of each guideline by the Monte Carlo (MC) simulation. In the stochastic analysis, once the simulations are run, several response surfaces of design variables are explored for the most influential inputs. Moreover, the tool can be used to verify the qualitative analysis (see **Figure 4**).

The tool developed has many advantages for the analysis and comparison of the design guidelines. First, the tool allows an automatic generation of multiple scenarios. Secondly, the tool allows the possibility to apply simultaneously a same size of samples (multiple scenarios) to multiple design guidelines, allowing the possibility to compare the response surfaces on these scenarios. Finally the tool has been coded in a flexible way, so that different guidelines can be plugged-in and compared to each other.

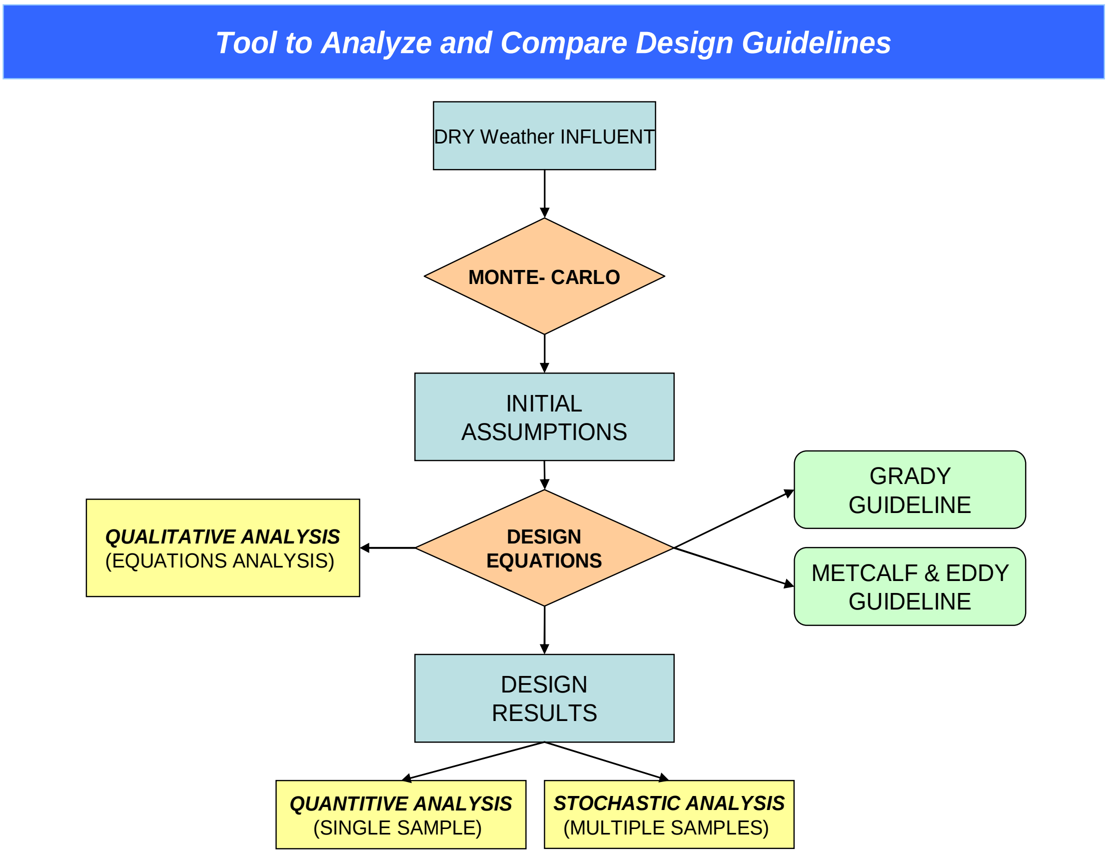


Figure 4. Layout of the automatic tool developed to simultaneously analyze and compare multiple design guidelines. In this case, the guidelines selected are Metcalf & Eddy and Grady. The *blue boxes* represent the input variables (*Dry influent* and *Initial Assumptions*) and output variables (Design variables) obtained trough the tool developed. The *orange boxes* are the algorithms used in the tool to generate ranges of values (*Monte- Carlo simulation*) and to obtain the design variables (*Design equations*), The *green boxes* are the guidelines selected for the case study. The *yellow boxes* are the different analyses conducted in the post-process.

2.3.2. Monte-Carlo (MC) Simulations

MC simulation methods are a class of computational algorithms that rely on repeated random sampling. MC simulation involves 3 steps: (1) Specifying ranges for the model inputs *i.e.* in this case study initial assumptions *[A]*, (2) sampling from the input ranges and (3) propagating the sampled values through the model to obtain a range of values for the output *i.e*. the design variables.

2.3.2.1. Specification of the inputs

In this case study the range of values considered for the initial assumptions *[A]* during the activated sludge plant sizing are the input factors. The range of values of the initial assumptions *[A]* are characterized using uniform probability distributions (**Table 3**). These distributions are assumed to characterize either the lack of knowledge by the design engineer (influent fractions) or the ranges of values that various stakeholders are considering for their choices (safety factors, operational conditions, effluent requirements) (**Figure 3**). In the first case, *i.e.* influent fractions, the total organic load is considered to be known, but the different biodegradable (f_S_B, f_X_B and f_X_{OHO}) and non-biodegradable (f_S_U and $f\_X_{U,inf}$) fractions are uncertain (notation as presented in **Corominas *et al*., 2010**). The role of f_X_B (slowly biodegradable fraction) is not included in the table because it is calculated as the difference between 1 and the sum of the other organic fractions: $f\_X_B = 1 – (f\_S_B + f\_X_{OHO} + f\_S_U + f\_X_{U,inf})$. On the other hand, is necessary to do the same for the nitrogen load, where in this case the fraction calculated is the f_S_{NH} (ammonia-N fraction) by the difference between 1 and the sum of the soluble (f_S_{ND}) and particulate (f_X_{ND}) biodegradable organic nitrogen fractions: $f\_S_{NH} = 1 – (f\_S_{ND} + f\_X_{ND})$. In the second case the stakeholder choices refer to decisions to be made by owners, regulators and future operators. They include the effluent requirements (effluent ammonium and nitrate), the safety factor for the aerobic sections (SF_{AER}) and the operational conditions (the desired oxygen concentration in the bio-reactor). The authors are aware of other parameters with strong impact on plant design such as temperature, kinetics, stoichiometry, MLSS concentration in the reactor, settling properties amongst others. Some of these influences are further investigated in the scenario analysis while the others are assumed to be constant. In fact, the reader should be aware that this is an exemplary case study to test the methodology and that a full-fledged application is beyond the scope of this paper. Researchers applying this methodology will need to define which interactions they want to explore and to define appropriate distributions.

Table 3. Range of values of initial assumptions [A] expressed as uniform distributions characterised by default, upper and lower values (In order to full-fill the mass balance:

$f\_X_B = 1 - (f\_S_U + f\_S_B + f\_X_{U,inf} + f\_X_{OHO})$; $f\_S_{NH} = 1 - (f\_S_{ND} + f\_X_{ND})$

Initial assumption [A]	**Symbol**	**Default value**	**Lower value**	**Upper value**	**units**
Influent fractions					
Soluble inert organic	f_S_U	0.09	0.05	0.14	-
Readily biodegradable	f_S_B	0.16	0.08	0.24	-
Particulate inert organic	$f\_X_{U,inf}$	0.12	0.06	0.18	-
Heterotrophic biomass	f_X_{OHO}	0.11	0.06	0.17	-
Soluble biodegradable organic-N	f_S_{ND}	0.14	0.07	0.22	-
Particulate biodegradable organic-N	f_X_{ND}	0.21	0.10	0.33	-
Effluent requirements					
Effluent ammonium	S_{NHX}	2	0.5	6	$gN \cdot m^{-3}$
Effluent nitrate	S_{NOX}	6	5	10	$gN \cdot m^{-3}$
Safety factors					
Aerobic section	SF_{AER}	1.5	1	1.5	-
Operational conditions					
Dissolved oxygen in the aerobic zone	S_{O2}	2.0	0.5	4	$(-gCOD) \cdot m^{-3}$

2.3.2.2. Sampling from the input factor ranges

The input space is sampled using the Latin hypercube method (LHS) (**McKay, 1979; Iman *et al*., 1981**). The LHS method is a stratified sampling technique that enables covering the entire sampling space with a lower number of samples compared to random sampling. In this study, a sample size of 1000 is applied. Each Latin hypercube sample contains one randomly selected value from each of the previously defined probability distributions. It is important to highlight that uncorrelated sampling is assumed in this case study. The authors are aware that some correlation is possible between the input choices e.g. low effluent S_{NHX} and S_{NOX}. Nevertheless, for simplicity purposes input ranges are assumed to be independent.

2.3.2.3. Propagation the sampled values through the model to obtain a range of values for the output

For each sample of initial assumptions *[A]* the design variables *[X]* are computed with the Metcalf & Eddy equations: *[X] =f([A]).* The solution of the model, for all the parameter combinations, results in a distribution for the desired design criteria *[X].*

2.4. Analysis and Comparison of Design Guidelines

2.4.1. Introduction

The main reason to use the methodology defined to analyze and compare design guidelines is to obtain a complete understanding of the differences in the design responses. Due to that, it is convenient before any analysis of the design responses to first have a prior knowledge of design guidelines equations in a qualitative level. Once the qualitative analysis is conducted, the following step in the study of the design responses is structured in a quantitative and stochastic analysis. The quantitative analysis consists on the study of the design responses for a specific scenario (one sample), and the stochastic analysis is the study of these design responses for multiple scenarios (multiple samples). **Figure 5** presents a scheme of the different levels of analysis, qualitative, quantitative (1 sample) and stochastic (multiple samples using MC).

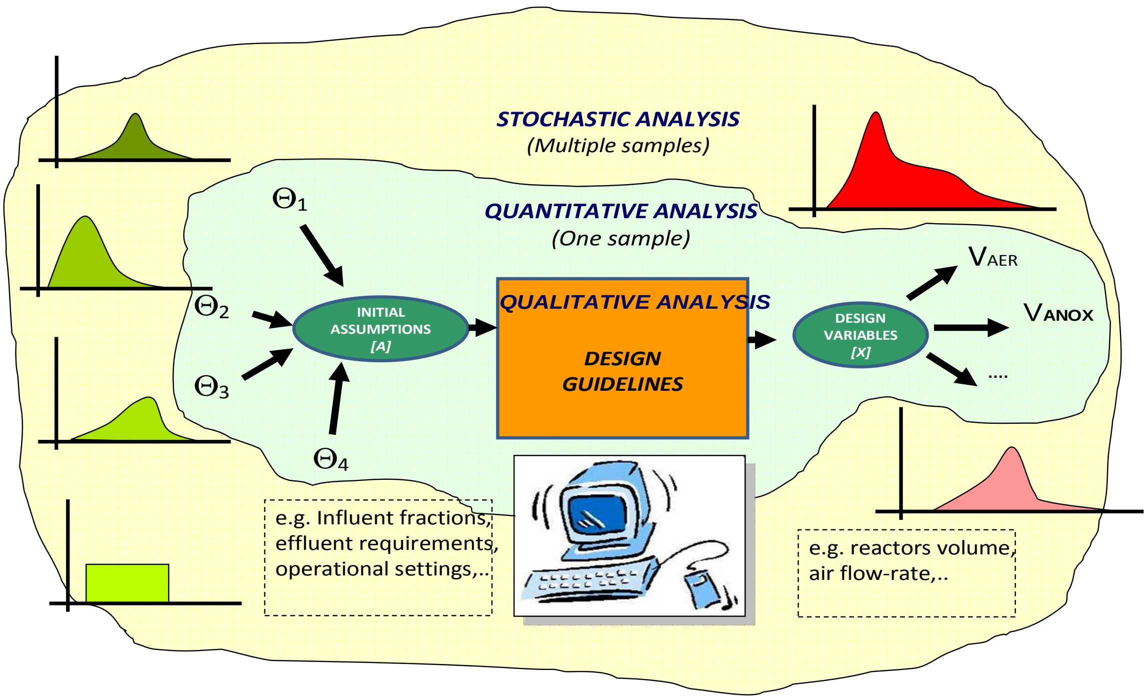


Figure 5. General scheme of the different analysis levels in terms of sample size.

2.4.2. Qualitative analysis

With the objective to identify the principal characteristics and differences of the design guidelines, this analysis consists in the study and understanding of the approach, procedure, and equations used in the design guidelines for the process configuration selected. To achieve these objective, is necessary to: i) understand the basis of the biological nitrogen removal process in activated sludge wastewater treatment plants, ii) understand the process configuration of the case study (MLE configuration), iii) analyze equation by equation of each design guidelines, and iv) identify the principal characteristics and differences of the designs. Once the analytical comparison of the design guidelines is finished it is possible to define the scenarios for the following levels of analysis (quantitative and stochastic analysis).

2.4.3. Quantitative Analysis (Single Sample)

The objective of this study lies in the interest to study the response of the design variables *[X]* in a specific case using a single sample of initial assumptions *[A]* (see **Figure 5**). In this case, the influent wastewater profile and composition, the effluent requirements, the operational settings, and the safety factors have the default values shown in the **Table 3**. The scenario operating temperature is 15ºC, and the wastewater to be treated has the default values profile and composition as in the Benchmark Simulation Model No 1 (BSM1) (Copp 2002) as explained before.

2.4.4. Stochastic analysis (Multiple Samples)

2.4.4.1. Single Scenario

The next step is the study of the distribution and response surfaces of the design variables *[X]* for a sample size of 1000 as initial assumptions *[A]*, using the Latin Hypercube sampling (LHS) technique to generate values from the input ranges, which are then propagated by Monte- Carlo (MC) simulation to the non-linear implicit algebraic equations of the designs (see **Figure 5**). The range of values used in this case study for the initial assumptions *[A]* are defined in **Table 3**. The operating temperature of this case-study is maintained in 15ºC as for the quantitative analysis. The interest lies on the comparison analysis of: i) the ranges and distributions of the design variables *[X]*, i.e. average value, maximum and minimum values, median, and first (Q1) and third quartile (Q3), ii) the cumulative distribution of the design variables *[X]*, and iii) the response surfaces that show a graphical representation of the variation and dependencies of the design variables when the most influential design assumptions are changed. Note the interest of this type of analysis using MC simulation due to the possibility to study the response surfaces in different scatters (2D and 3D) of the design variables versus any variable involved in the process, i.e. influent wastewater compositions, operational settings, effluent requirements, and internal design variables involved in the design.

2.4.4.2. Multiple Scenarios (Scenario analysis)

The scenario analysis is used to answer questions such as *what would happen if* - evaluating the effect of changing pre-defined conditions. In this case study, the comparison analysis is so interesting once the analytical, quantitative, and stochastic analysis comparisons are done. This kind of analysis allows for the possibility to study the real response of the designs once the knowledge level is high enough, derived from the previous analysis (analytical, quantitative, and stochastic), by changing pre-defined conditions of the previous scenarios. In this case-study, the interest lies in the response analysis of the design variables for the increasing of the aerobic sludge residence time (SRT_{AER}), because the qualitative and quantitative analyses indicated this is the most critical parameter for activated sludge design (SRT affects the treatment process performance, tank volume, sludge production, and oxygen requirements). Moreover, SRT is the main parameter used by operators to control activated sludge process.

The three scenarios defined are: S1) Operating temperature of 15ºC and no safety factors applied, S2) Operating temperature of 15ºC and safety factors applied, S3) Operating temperature of 10ºC and safety factors applied. Table 4 shows the summary scenarios characteristics

Table 4. Summary scenarios characteristics for the Scenario Analysis.

Summary Scenario Characteristics (Scenario Analysis)		
Scenario	**Temperature (ºC)**	**Safety Factor (-)**
Scenario 1 (S1)	15	1.0
Scenario 2 (S2)	15	1.0 – 1.5
Scenario 3 (S3)	10	1.0 – 1.5

3. RESULTS

3.1. Qualitative analysis

3.1.1. General approach

The general approach to design a modified Ludzack-Ettinger (MLE) configuration consists in the design of these aerobic and anoxic process by the following steps. First, the reactor aerobic zone volume (V_{AER}) is sized on the basis of the net specific growth rate of nitrifying organisms to maintain the chosen sludge residence time to achieve the ammonia-N concentration required in the effluent. Next, the required internal recycle flow-rate (Q_{INTR}) is calculated through a mass balance which includes the nitrate produced in the aerobic zone, the nitrate in the return activated sludge and the desired nitrate level in the effluent. Then the reactor anoxic zone volume (V_{ANOX}) is designed on the basis of the growth rate of denitrification, by comparing the nitrate produced in the aerobic zone to the nitrate which can potentially be removed. Finally the air flow rate (Q_{AIR}) is quantified based on the difference between the oxygen required (for carbon removal and nitrification) and the oxygen saved by denitrification.

The main differences found between the two design guidelines are related to the calculation of the SRT and the approach to obtain the volumes of the aerobic and anoxic reactors.

3.1.2. SRT calculation

The SRT represents the average period of time during which the sludge has remained in the system, and is used for the operators as a control parameter of the plant. To maintain a given sludge residence time (SRT), the excess activated sludge produced each day must be wasted. SRT is an important parameter for activated sludge process design, because it is used in all the following steps of the design process. It affects the treatment process performance, aeration tank volume, sludge production, and oxygen requirement of the process. The desired SRT (aerobic SRT) is selected by nitrification for the removal of nitrogen to achieve a required ammonia-N concentration in the effluent.

The two design guidelines selected shows a different approach to calculate the SRT by the different application of the DO term (τ_{DO}) in the autotrophic growth Monod expression.

$$\tau_{DO} = \frac{S_{O2}}{K_{O2,ANO} + S_{O2}} \qquad \text{(Eq. 1)}$$

Where S_{O2} = dissolve oxygen concentration (DO), g/m^3

$K_{O2,ANO}$ = half-saturation coefficient for DO, g/m^3

3.1.2.1. Grady approach to calculate the SRT

Grady design guideline uses an approach commonly used in the engineering fields, where the DO term (τ_{DO}) is applied to both growth and death rates terms, using the given Eq. 2:

$$\frac{1}{SRT_{AEROBIC}} = \left(\mu_{ANO,Max} \left(\frac{S_{NH_X}}{K_{NH_X,ANO} + S_{NH_X}} \right) - b_{OHO} \right) \cdot \tau_{DO} \qquad \text{(Eq. 2)}$$

Where $\mu_{ANO,Max}$=maximum specific growth rate of nitrifying bacteria, g new cells/(g cells·d)

b_{OHO} = endogenous decay coefficient for nitrifying organisms, g TSS/ (g TSS·d)

S_{NH_X} = nitrogen concentration, g/m^3

$K_{NH_{X,ANO}}$ = half-velocity constant, substrate concentration at one-half the maximum specific substrate utilization rate, g/m^3

3.1.2.2. Metcalf & Eddy approach to calculate the SRT

Otherwise, Metcalf & Eddy design guideline uses another approach which is the defined in the ASM No. 1 models, applying the *DO* term only in the growth rate of the nitrifying organisms. The equation is given below (Eq. 3):

$$\frac{1}{SRT_{AEROBIC}} = \mu_{ANO,Max}\left(\frac{S_{NH_X}}{K_{NH_X,ANO} + S_{NH_X}}\right)\tau_{DO} - b_{OHO} \qquad \text{(Eq. 3)}$$

The consequences to use different approach derives that the aerobic SRT selected in the Metcalf & Eddy design guideline will be always higher than Grady design guideline (for the same ammonia-N concentration effluent quality), which must be take into account in the results analysis of the following analysis levels (quantitative and stochastic analysis).

3.1.3. Design of the aerobic and anoxic volumes

To carry out the estimation of the aerobic and anoxic volumes both design guidelines coincide in the main idea:

The design of the aerobic volume starts with the selection of the SRT required to achieve a certain degree of nitrification that is limited by the desired ammonia-N concentration in the effluent (also used for the estimation of the nitrate-N produced). Then, the design of the anoxic volume requires a nitrogen mass balance to determine the amount of nitrate that is produced in the aeration zone and the internal recycle flow rate (Q_{INTR}) required to achieve the desired effluent nitrate concentration. However, the two design guidelines use different approaches to calculate the fraction of the total volume that is aerobic (V_{ANOX}) and anoxic (V_{ANOX}), and the way the oxygen demand (Q_{AIR}) is calculated.

3.1.3.1. <u>Grady Design Guideline</u>

To obtain the aerobic and anoxic tank volumes, Grady design is based in the ASM No 1. models, relating the nitrification and denitrification rates to fundamental biokinetics. First, the SRT_{AER} is selected by assuming a certain nitrification rate (Section 3.1.2.1**).** Then, the anoxic design consists to select the SRT_{ANOX} to ensure the removal of a specific mass of nitrate-N and a specific mass of biodegradable organic matter. The estimation of the organic substrate utilization and associated nitrate-N reduction requires two steps, one for readily biodegradable substrate and one for slowly biodegradable substrate.

Once both SRTs are selected, the required total volume (sum of V_{ANOX} and V_{AER}) in the process is sized on the basis of the total SRT (sum of SRT_{AER} and SRT_{ANOX}), the desired mixed liquor suspended solids (MLSS) concentration and the total mass of solids that has to be removed to maintain the total SRT (see Eq. 6):

$$SRT \approx SRT_{TOTAL} = SRT_{ANOX} + SRT_{AER} \qquad \text{(Eq. 4)}$$

Where SRT_{TOTAL} = process sludge residence time, d.

SRT_{ANOX} = anoxic sludge residence time, d.

SRT_{AER} = aerobic sludge residence time, d.

$$V \approx V_{TOTAL} = V_{ANOX} + V_{AER} \qquad \text{(Eq. 5)}$$

Where V_{TOTAL} = sum of the reactor tank process (aerobic and anoxic zones), m^3

V_{ANOX} = anoxic reactor volume, m^3.

V_{AER} = aerobic reactor volume, m^3

$$SRT = \cdot \frac{V \cdot X}{Q_W \cdot X_r + (Q - Q_W) X_e} \qquad \text{(Eq. 5)}$$

Then, the respective zone volumes are determined by the fraction of the SRT zone by the total SRT (Eq. 7 and Eq. 8):

$$V_{ANOX} = \cdot V \cdot \frac{SRT_{ANOX}}{SRT_{TOTAL}} \qquad \text{(Eq. 6)}$$

$$V_{AER} = V - V_{ANOX} \qquad \text{(Eq. 7)}$$

The air flow rate (Q_{AIR}) and the sludge wasted (W_{MT}), are estimated by means of the total SRT (SRT_{TOTAL}). **Figure 6** shows a schematic diagram where the SRT interpretation used for the MLE configuration in Grady design is represented.

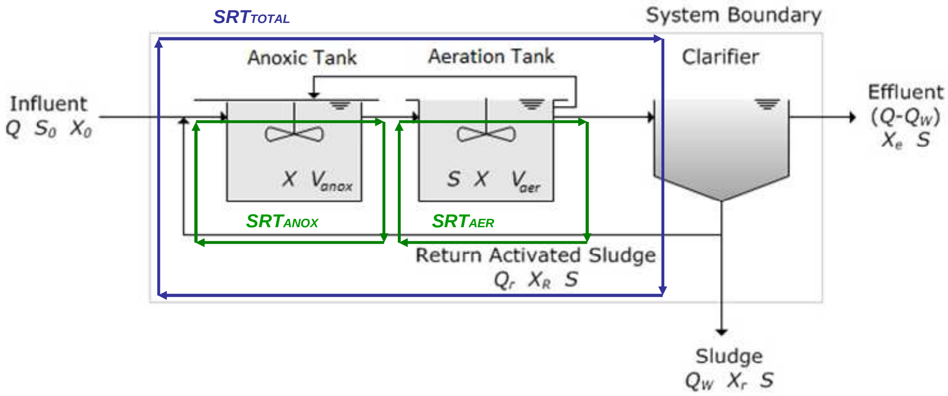


Figure 6. Schematic diagram where is represented the SRT interpretation used for the MLE configuration in Grady design.

3.1.3.2. Metcalf&Eddy Design Guideline

To design the MLE configuration, Metcalf & Eddy design uses the following procedure, designing first the aerobic zone, without accounting the existence of a previous anoxic process, and then designing the anoxic zone.

First, the reactor zone volume (V_{AER}) is sized on the basis of the SRT_{AER}, the desired mixed liquor suspended solids (MLSS) concentration and the total mass of solids that has to be removed to maintain the chosen SRT_{AER} by the using Eq. 6. This is the same approach used in Grady design, but substituting the terms SRT_{AER} for $SRT_{TOT,}$ and V_{AER} for V_{TOTAL}:

$$SRT = \cdot \frac{V \cdot X}{Q_W \cdot X_r + (Q - Q_W) X_e} \qquad \text{(Eq. 8)}$$

Once the aerobic zone is designed (having a value for V_{AER} and the nitrate-N produced) the design of the anoxic tank volume (V_{ANOX}) is conducted, with the purpose to remove the nitrate-N produced in the aerobic zone to complete the nitrogen removal, reducing the nitrate-N to nitrogen gas (N_2) by denitrification.

The anoxic design selected for the estimation of the reactor anoxic volume (V_{ANOX}) consists in comparing the nitrate-N fed from the aerobic zone to the nitrate that must be removed to accomplish the nitrate-N requirement in the effluent by a deskopt design approach. This is based on using a specific denitrification rates (SDNR), which is the nitrate reduction rate in the anoxic tank normalized to the MLSS concentration. Selecting the required SDNR by the hydraulic retention time (HRT), the amount of nitrate removed in the anoxic tank can be calculated.

Only the aerobic basin volume and mixed liquor concentration are used to compute the sludge wasting (W_{MT}) and the air flow rate (Q_{AIR}) by the aerobic SRT (SRT_{AER}). **Figure 7** shows diagram scheme about the SRT interpretation used to design the MLE configuration.

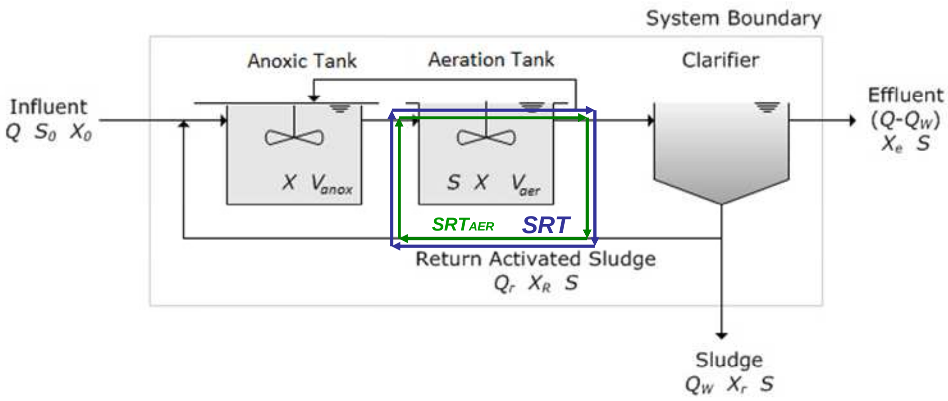
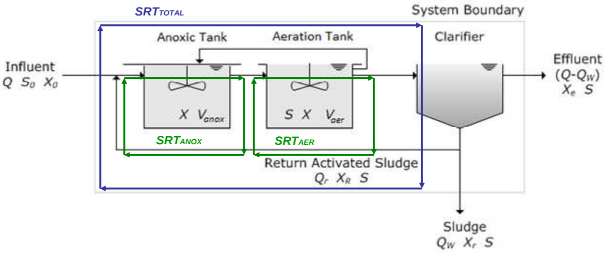


Figure 7. Diagram scheme about the SRT interpretation used to design the MLE configuration by Metcalf & Eddy guideline.

As a result, the MLE configuration design procedure used by Metcalf & Eddy guidelines seems to not account in the design of the aerobic tank that part of the organic matter is first removed in the anoxic zone (designing first the aerobic zone by estimating the aerobic volume and then the anoxic volume). Moreover, the sludge production and the oxygen requirement are estimated by the sum of the SRT_{AER} and SRT_{ANOX} (SRT_{TOTAL}) in Grady design and only by the SRT_{AER} in Metcalf & Eddy design. The **Figure 8** show an scheme of the estimation of the aerobic and anoxic volumes for the guidelines selected.

Grady design guideline



Metcalf & Eddy design guideline

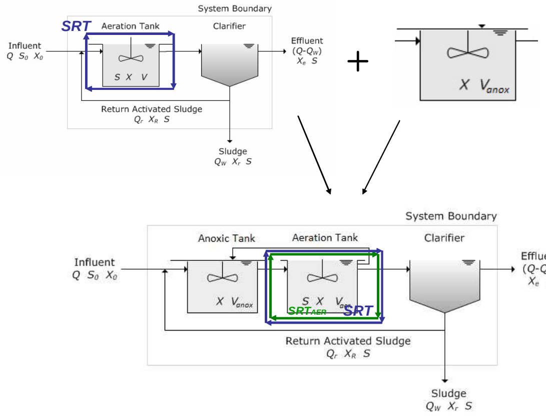


Figure 8. Scheme of the estimation procedure the aerobic and anoxic volumes design.

3.2. Quantitative analysis

As mentioned before (Section 2.4.3), the objective of this analysis lies in the interest to study the differences of the design variables *[X]* obtained from the design of a WWTP using Metcalf & Eddy and Grady guidelines in specific case (one sample), for a temperature of 15ºC, using the operating conditions and the wastewater characterization values defined in the **Table 5**. The design variables are reported in **Table 6**.

The results of the design exercises (showing the values for the design variables) conducted for Grady and Metcalf & Eddy are presented in **Table 6.** At first sight, it is important to highlight that the total volume required (V_{TOTAL}) in the different designs to accomplish the desired effluent quality have practically the same values (around 11.150 m^3). However, significant differences between aerobic (V_{AER}) and anoxic (V_{ANOX}) volumes are obtained for the different guidelines. In the Grady design, the distribution of the aerobic and anoxic volumes is approximately 50% for each zone (around 5.550 m^3). On the other hand, Metcalf & Eddy design gives different percentage distribution for the sizing tank, giving the 25% (2.874 m^3) to the anoxic tank (V_{ANOX}) and the rest (75%) to the aerobic tank (V_{AER}). Therefore, Grady design assigns lower aerobic volume (V_{AER}) and higher anoxic volume (V_{ANOX}) than Metcalf & Eddy design. This is mainly explained by the different approach used in the estimation of the tank volumes (as explained in the qualitative analysis).

Grady guideline design considers that the removal of organic matter is conducted in both zones. The majority of organic matter is consumed in the anoxic zone for denitrification, and the rest is degraded in the aerobic zone. On the other hand, Metcalf & Eddy designs the aerobic reactor considering that organic matter is removed there. This results with oversized aerobic reactors, because just a small fraction of organic matter will enter the aerobic reactor.

The results also show the effects of calculating the aerobic SRT differently (SRT_{AER}), obtaining higher values with the Metcalf & Eddy design mainly explained by the use of the DO Monod term. It is important to stress that higher SRT_{AER} results with higher nitrate-N production (S_{NO}) that will require higher internal recycle flow-rates (Q_{INT}), and therefore more nitrate-N is to be reduced in the anoxic reactor (see **Table 6**).

Significant differences in the sludge production ($W_{M,T}$) are observed for both guidelines. SRT is a parameter used to calculate sludge production. Metcalf & Eddy design (3.097 kg/d) uses the SRT_{AER} (8,1 d) and Grady design (2.230 kg/d) uses the total SRT (15 d), which is the sum of the SRT_{AER} (7,5 d) and SRT_{ANOX} (7,436 d) . The different values of SRT also explain the differences in the oxygen demand (Q_{AIR}).

Finally, one would expect that lower nitrate recycle values would result in smaller anoxic tank volumes. However, a lower nitrate recycled (Q_{INTR}) value is obtained with Grady (84.756 m^3/d compared to 91.870 m^3/d) design requires a larger anoxic tank volume (5.550 m^3) compared to Metcalf & Eddy design (2.847 m^3). This gives a first impression that Metcalf & Eddy anoxic design is very optimistic in terms of denitrification rates, and shows that for the same initial design assumptions (same inputs) the anoxic designs do not yield the same results.

Table 5. Summary of the operation conditions and influent wastewater characterization.

Operation Conditions and Influent wastewater Characterization		
Characteristics	**Units**	**Values**
Influent Wastewater Characterization		
Q	m^3/d	18.336
BOD_5	mg/l as COD	183,54
sBOD	mg/l as COD	83,075
COD_{TO}	mg/l as COD	360
sCOD	mg/l as COD	127,81
rbCOD	mg/l as COD	66,50
TSS	mg/l as TSS	195,89
VSS	mg/l as TSS	183,48
TKN	mg/l as N	51,47
NH_4-N (ammonia-N)	mg/l as N	30,34
Effluent Requirements		
Effluent ammonium (S_{NHX})	mg/l as N	2
Effluent nitrate (S_{NOX})	mg/l as N	6
Safety Factors		
Aerobic Section	-	1.5
Operational Conditions		
Dissolve Oxygen in the Aerobic Zone	mg/l as O_2	2
MLSS concentration	mg/l	3000
MLSS concentration outlet clarifier	mg/l	8000

Table 6. Summary of the design variables in the quantitative comparison, using the default vaules defined in Table 2 as initial assumptions. In bold, the design variables *[X]*.

Design variables	**Design guidelines**		
	Metcalf & Eddy		**Grady**
SRT_{AER}	8,1 d	>	7,5 d
SRT_{ANOX}	-	-	7,436 d
SRT_{TOTAL}	8,1 d	<	15 d
S_{NO}	39,7 mg/l	>	37,4 mg/l
$W_{M,T}$	3.097 kg/d	>	2.230 kg/d
V_{AER}	8.345 m^3	>>	5.576 m^3
V_{ANOX}	2.847 m^3	<<	5.550 m^3
V_{TOTAL}	11.192 m^3	>	11.125 m^3
Q_{INTR}	91.870 m^3/d	>	84.756 m^3/d
Q_{AIR}	4.492 kg/d as O_2	<	5.022 kg/d as O_2

3.3. Analysis stochastic

3.3.1. Single Scenario

3.3.1.1. Monte-Carlo (MC) Simulations

The stochastic analysis consists in the study of the design variables *[X]* obtained by propagating the initial assumptions *[A]* from **Table 3** using the Monte- Carlo (MC) simulation (multiple samples). The temperature assigned in the scenario is the same as in the quantitative analysis (15 ºC). In this study, the sample size is 1000, and the average time to run this analysis (1000 MC simulations) on a regular PC is around 7 minutes. **Table 7** summarizes the ranges of the design variables *[X]* obtained from the 1000 design exercises. The ranges are characterized by average value, maximum and minimum values, median, and first (*Q1*) and third (*Q3*) quartile.

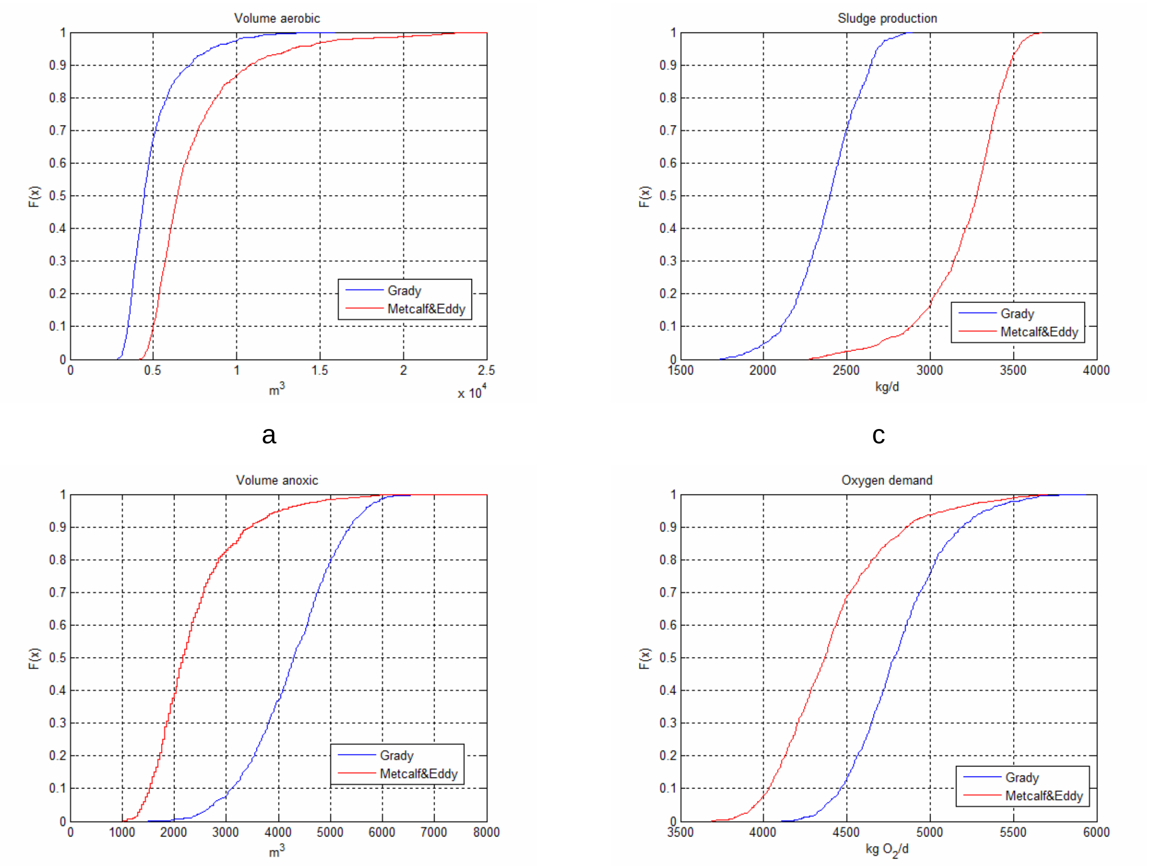
Table 7. Average values, maximum and minimum values, quartiles Q1 and Q3 and Q3-Q1 for the design variables [X] obtained in the Monte Carlo analysis.

	Design variable [X]							
	V_{AER} (m^3)		**V_{ANOX} (m^3)**		**Q_{AIR} ($m^3 day^{-1}$)**		**Q_{INTR} (kg O_2 day^{-1})**	
	M&E	***Grady***	***M&E***	***Grady***	***M&E***	***Grady***	***M&E***	***Grady***
Average value	7.498	4.915	2.387	4.538	4.410	4.865	66.426	59.880
Maximum value	101.090	17.527	20.800	6.935	5.844	5.838	131.950	109.150
Minimum value	4.148	2.775	1.135	2.000	3.719	4.114	33.724	28.590
Percentile 25 (Q1)	5.583	3.833	1.788	3.930	4.180	4.673	49.845	43.920
Median	8.024	5.378	2.682	5.134	4.601	5.043	81.562	74.294
Percentile 75 (Q3)	11.998	8.239	3.954	8.484	8.542	9.510	112.664	100.635
Q3-Q1	6.415	4.406	2.166	4.554	4.362	4.837	62.819	56.715

The variability in the design variables is explained by the differences between Q3 and Q1 (see **Table 7).** Overall, we can observe a large impact of the initial design assumptions on tank volumes (V_{AER} and V_{ANOX}) and pump sizing (Q_{AIR} and Q_{INT}). The anoxic tank variability is larger for Grady design (4.554 m^3) compared to Metcalf &

Eddy design (2.166 m^3), but lower in the aerobic tank (4.406 m^3 for Grady design to 6.415 m^3 for Metcalf Eddy design).

The cumulative distribution of the most important design variables is presented in **Figure 9**. Aerobic volume (V_{AER}), sludge production (W_{MT}) and oxygen demand (Q_{AIR}) cumulative distribution follow a similar pattern, with constant differences in the frequencies of the different volumes. Grady obtains lower aerobic volumes for all simulations, lower sludge production and higher oxygen demand. On the other hand, the cumulative distribution of the anoxic volume (V_{ANOX}) (**Figure 9b**) reflects the differences in the anoxic design by non-similitude in the variation throughout the cumulative sample. Grady results with larger anoxic volumes.



a c

b d

Figure 9. Cumulative distribution of the (a) aerobic volume, (b) anoxic volume, (c) sludge production, and (d) oxygen demand.

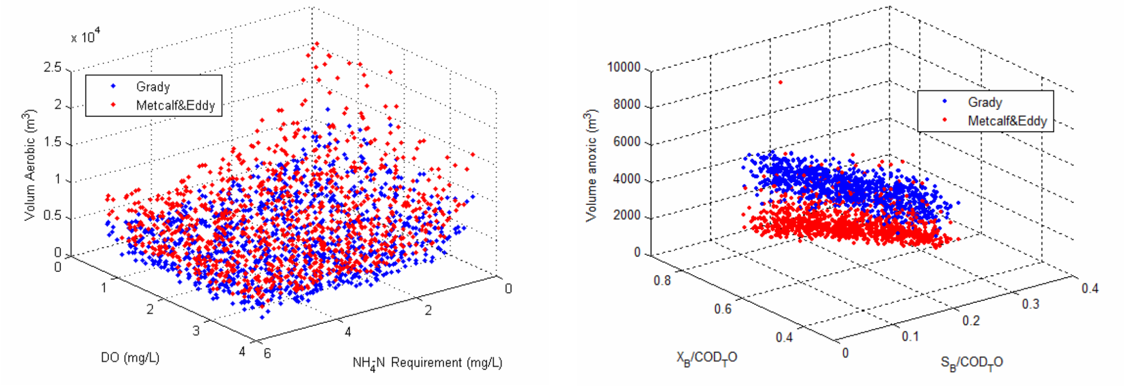
It is important to highlight that in the Metcalf & Eddy design about 10% of the aerobic volume values are between 10000 and 20000 m^3, reaching non-realistic maximum values of 101.090 m^3. These outliers correspond to design exercises with low DO concentrations (0.5 mg/l) and the non-realistic values are explained by the calculation of the SRT which is more sensitive at low DO concentrations in the Metcalf & Eddy approach.

The stochastic analysis confirms the results obtained with the quantitative analysis in the sense that the distribution of the design volumes remains in the same ranges (aerobic volumes respect to the total of 75% in Metcalf & Eddy and 50% in Grady). Moreover, the anoxic volumes (V_{ANOX}) by Grady design still higher (50% of the total volume required in the process) than Metcalf & Eddy guideline (25% of the total volume required in the process). The internal recycle flow-rate (Q_{INTR}) remains lower in the Metcalf & Eddy design (see **Table 7**).

3.3.1.2. Response Surface Analysis

The interpretation of the results includes the creation of high-dimensional response surfaces (one for each design variable), representing a design variable *X* as a function of initial design assumptions *[A]*. The creation of these response surfaces allows a “regional” instead of a “local” analysis of the design. In this way it is possible to study the variation of the different design variables (V_{AER}, V_{ANOX}, Q_{AIR}, Q_{INTR}) as function of the ranges of the initial assumptions; i.e. missing knowledge, engineering choices, setting of effluent requirements; allowing a better understanding of the design space as is observed in the analysis done.

Figure 10 shows a 3D scatter plot which displays the combined influence of the identified two most “influential” assumptions for both aerobic (V_{AER}) and anoxic (V_{ANOX}) volumes. It is observed that low effluent requirements (NH_4-N requirement) and low oxygen concentrations (DO) lead to large aerobic volumes (V_{AER}) and vice versa (see **Figure 10a**). On the other hand, low influent readily biodegradable (S_B/COD_{TOT}) and high influent slowly biodegradable (X_B/COD_{TOT}) lead to larger anoxic volumes (V_{ANOX}) (see **Figure 10b**).



a b

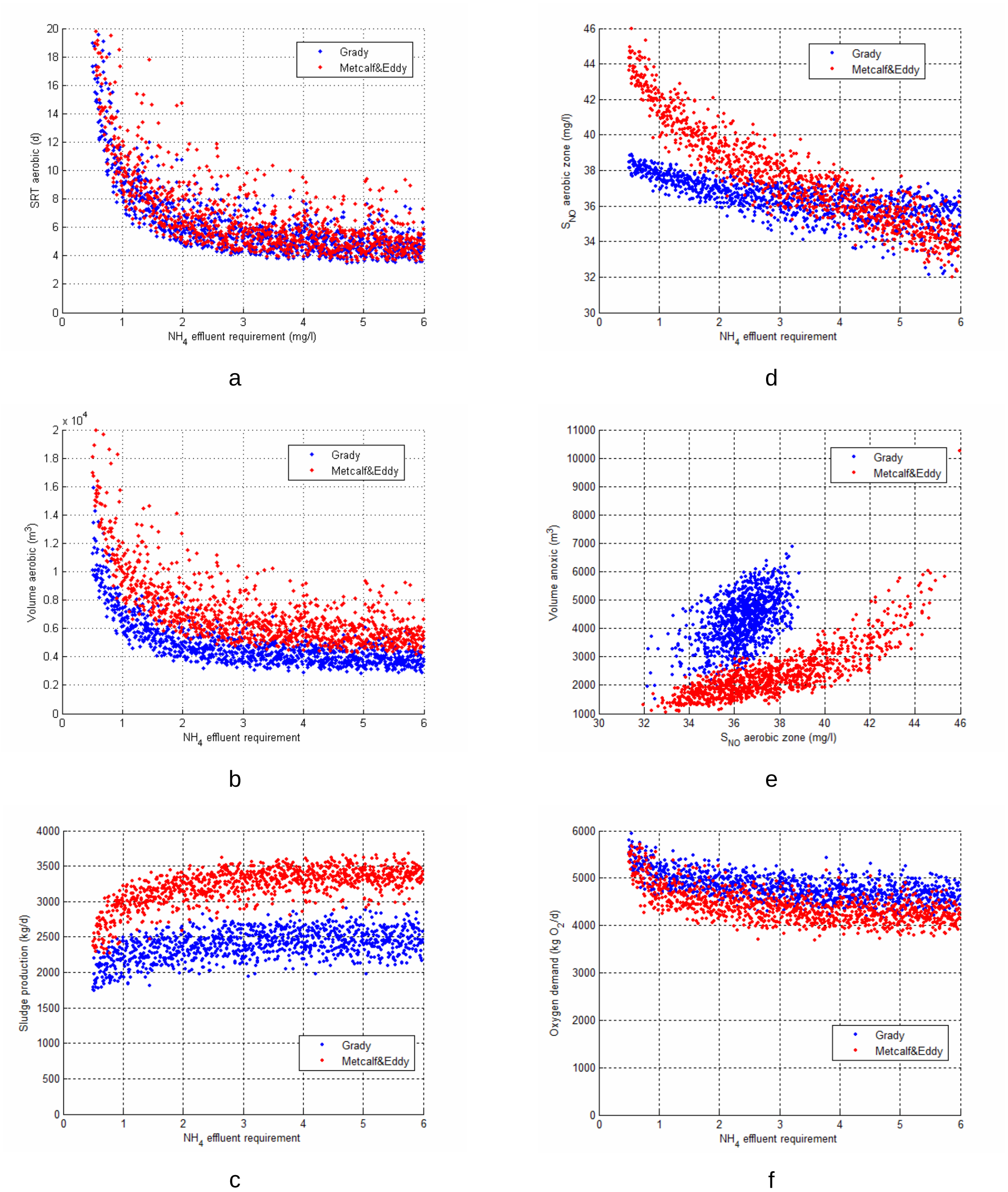
Figure 10. Combined influence of the most influential initial assumptions for (a) aerobic and (b) anoxic volume.

On the other hand, the response surfaces also can be represented in a 2D scatter plot which displays internal design variables or initial assumptions for any design variable *[X]* of the guidelines. The most interesting plots are presented in **Figure 11**.

Figure 11a and **Figure 11b** show in more detail the response of Metcalf & Eddy approach to the selection of SRT and the aerobic volume on the ammonia-N requirement. It can be seen that for a desired ammonia-N requirement in the effluent, Metcalf & Eddy will always obtain higher SRT_{AER} and V_{AER}.

Figure 11d shows the different responses of the nitrate-N concentration formed in aerobic zone. At lower ammonium-N effluent requirements higher production of nitrate-N is obtained in Metcalf & Eddy. This guideline assumes that a higher percentage (compared to Grady) of the influent TKN is available for the autotrophic organisms responsible to transform to ammonium-N into nitrate. Moreover, the larger aerobic SRT values of the Metcalf & Eddy design also help to convert more ammonia-N to nitrate-N.

Figure 11e reaffirms as in the previous analysis (qualitative, quantitative and cumulative distributions) that the anoxic designs selected by the guidelines do not give the same response for the same initial assumptions. The figure also shows that Metcalf & Eddy design is more sensitive to the nitrate-N formed in the aerobic zone (S_{NO}), while Grady anoxic design do not show a clear dependence.



a d

b e

c f

Figure 11. Combined influence of the most influential initial assumptions for (a) aerobic SRT, (b) aerobic volume , (c) sludge production, (d) nitrate formed in the aerobic zone, (e) anoxic volum, (f) and oxygen demand of the process.

To conclude, **Figure 11c** and **Figure 11f** show the effects of higher SRT, where due to the microorganisms resides longer time in the system, the sludge production decreases by endogenous decay and the oxygen demand increases by the consuming of more oxygen by bacteria. In this sense, the use of the aerobic SRT (as

Metcalf & Eddy guideline) or total SRT (as Grady guideline) to estimate the sludge production and oxygen demand explains the differences observed in the figures.

3.3.2. Multiple Scenarios (Scenario analysis)

This section analyzes how the results from MC simulations are affected by changing some of the pre-defined conditions of the previous scenarios. The interest lies in the response analysis of the design variables that indirectly influence the calculation of the aerobic sludge residence time (SRT_{AER}), because the qualitative and quantitative analyses indicated that this is the most critical parameter for activated sludge design. Thus, three scenarios are defined depending on temperature and the use of safety factors and the results are compared to the reference situation (S2) which corresponds to the results of the stochastic analysis results.

Table 8 summarizes the ranges of the design variables *[X]* obtained from propagating the initial assumptions *[A]* in the three scenarios (S1, S2, and S3), by the using of the MC simulation. The ranges are characterized by the average and percentage of volume distribution values.

The first scenario (S1) shows the effects of not applying safety factors, which leads to a substantial decrease in the following design variables (V_{AER}, V_{ANOX}, Q_{AIR}, Q_{INT}). The variation of these is similar between the guidelines. The decrease of the SRT_{AER} also affects the Q_{AIR} and Q_{INT}, which are also reduced (less SRT_{AER}, less nitrate-N formed in the aerobic zone).

In the other scenario (S3), when the temperature is decreased, the contrary effect is observed, and with a higher magnitude. Volumes significantly increase (V_{AER} and V_{ANOX}) due to the increase of the SRT_{AER}. Furthermore, the percentage of aerobic volume increases up to the 81.4 % in Metcalf & Eddy design and up to 56.6 % in Grady design. Larger aerobic volumes are required at lower temperatures for both cases. Metcalf & Eddy design obtains mean aerobic volume of 12.000 m^3 and Grady 8.000 m^3 probably explained by the sensitivity to extreme operation conditions (e.g. low DO concentrations combined with low temperature).

Table 8. Summary of design variables *[X]* results obtained from propagating the initial assumptions [A] in the three scenarios by the using of the MC simulation. The ranges are characterized by average and median values.

	Design variable [X]							
	V_{AER} (m^3)		***V_{ANOX} (m^3)***		***Q_{AIR} (kg O_2 day-1)***		***Q_{INTR} (m^3day-1)***	
	M&E	***Grady***	***M&E***	***Grady***	***M&E***	***Grady***	***M&E***	***Grady***
S1: Without applying safety factors, at 15 ºC								
Average value	6.268	4.069	2.167	4.386	4.258	4.620	64.787	58.558
Percentage Volumes Distribution	74.3 %	48.13 %	25.7 %	51.87 %				
S2: Applying safety factors, at 15 ºC (Scenario reference)								
Average value	7.498	4.915	2.387	4.538	4.410	4.865	66.426	59.880
Percentage Volumes Distribution	76.8 %	52 %	24.2 %	48 %				
S3: Applying safety factors, at 10 ºC								
Average value	12.077	8.212	2.754	6.282	4.341	4.766	65.541	61.775
Percentage Volumes Distribution	81.4 %	56.6 %	18.6 %	43.4 %				

About the internal recycle (Q_{INTR}) and air (Q_{AIR}) flow-rates, in the same scenario (S3) the increases of the aerobic SRT (SRT_{AER}) derives a contrary effect as in the tanks volume response. The response of the internal recycle flow-rate (Q_{INTR}) is leaded to decrease in Metcalf & Eddy design and to increase in Grady design. For longer SRT, bacteria tends to consume more nitrogen to survive, due to the presence of the organic matter in the tank is reduced. If the SRT chosen is as longer as no more nitrogen (ammonia-N) is able to be reduced to nitrate, then an increase of the SRT derives a reduction of nitrate-N formed due to less nitrogen is available to nitrifiers. In base to that, the internal recycle flow-rate (Q_{INTR}) decreases in Metcalf & Eddy due to the nitrification approach gives higher SRT values than Grady nitrification approach. To conclude, the air flow-rate (Q_{AIR}) tends to decrease, affected probably for the consequences of the variance of the internal recycle flow-rate (Q_{INTR}) and the considerable increasing of the anoxic tank volume (V_{ANOX}), which this last derives to save more oxygen for the removal of organic matter, that do not have to be supplied in the aerobic process. The air flow-rate (Q_{AIR}) is always higher in Grady guideline due to it is estimated by the SRT_{TOTAL}, when Metcalf & Eddy design just account the SRT_{AER}.

3.4. Summary of the Results

In this section the principal characteristics and differences observed from the analysis and comparison done of Metcalf & Eddy and Grady design guidelines for the modified Ludzack Ettinger (MLE) configuration are summarized:

A. The design guidelines use different approaches to select the SRT for nitrification, with the consequence that the aerobic SRT selected in the Metcalf & Eddy design will always be higher than the Grady design, as a consequence the internal nitrate recycle pumping rate will also be higher. The Grady design approach is not as sensitive as the Metcalf & Eddy design approach to strict DO concentrations and ammonia-N requirements due to the application of the DO term in the Monod equation, conducting to a high and non-realistic SRT and aerobic tank volume.

B. The main and most important difference between the guidelines is the design of the aerobic tank volumes. Metcalf & Eddy designs do not account for the simultaneous removal of organics in the anoxic and aerobic processes.The aerobic tank is designed assuming that all organic matter is removed there. This is reflected in the quantitative and stochastic analysis results, in which the 75 % of the overall volume is attributed to the aerobic tank. On the other hand, the Grady design considers that the removal of organic matter is conducted in both zones, where the majority of organic matter is consumed first in the anoxic zone, and the rest is degraded in the aerobic zone, leading to equally distributed sizes (50 %) for the aerobic and anoxic tanks. Thus, the Grady design always leads to lower aerobic volumes, higher anoxic volumes, and slightly lower total volumes than Metcalf & Eddy design.

C. The lower nitrate recycle obtained with the Grady design requires a larger anoxic tank volume compared to the Metcalf & Eddy design. This gives an impression that the Metcalf & Eddy design is very optimistic in terms of denitrification rates, and shows that for the same initial design conditions the two anoxic designs lead to very different results.

D. One of the consequences of the different way to design the tank volume systems is that Grady design uses the total SRT of the system (sum of aerobic and anoxic SRT) and Metcalf & Eddy design the aerobic SRT to estimate the sludge production and the air flow rate. Therefore, the Metcalf & Eddy design will always exhibit higher sludge production and lower air flow rate than the Grady design. The anoxic SRT estimated with the Grady design has a similar magnitude to the aerobic SRT, leading to a total SRT value which is about two times the SRT obtained in the Metcalf & Eddy design.

From the scenario analysis it was possible to complement the entire evaluation process and to evaluate changes in the design and the relative importance of the initial design assumptions. It was observed that for a decrease of the temperature, the aerobic and anoxic volumes significantly increase mainly because of the increasing SRT and the nitrate produced in the aerobic zone. Furthermore, another effect of the decreasing of the temperature (S3) is that percentage of aerobic volume increases up to 81.4 % in Metcalf & Eddy design and up to 56.6 % in Grady design as a fraction of the total volumes. Finally, it was observed that when no safety factors are applied (S1), this leads to a substantial decrease of all the design variables, remaining the same tank percentage distribution as in the reference situation (S2).

A summary of the results is presented in **Table 9**. The table summarizes the analysis and comparison conducted for both guidelines for the MLE configuration, reflecting the results obtained for the most important design using the initial assumptions of the quantitative scenario (**Table 5**) and including the effects of two temperatures: 15ºC (left value) and 10ºC (right value). The arrows show the degree of variation from the scenarios selected, e.g. ↑/↓ means a small increase/decrease of the variable, ↑↑/ ↓↓ means a considerable increase/decrease, and – means no significant variation of the variable. The last right column (*Due to/ Reason*) gives reference information to understand these outcomes.

Table 9. Summary of the analysis and comparison done of the two guidelines selected (Metcalf & Eddy and Grady guidelines) for the modified Ludzack Ettinger (MLE) configuration using as initial assumptions the Table 5 values for the modification of the temperature (15ºC to 10ºC) in the two scenarios.

Design Variables	**Design guidelines**			**Due to/ Reason**
	Metcalf & Eddy		**Grady**	
SRT_{AER}	↑↑ (8,1 to 12.9 d)	>	↑↑ (7,50 to 12 d)	SRT nitrification approach (Reason A)
SRT_{ANOX}	↑ (- d)	<	↑ (7,4 to 9 d)	Design approach of aerobic and anoxic volumes (Reason B)
SRT_{TOTAL}	↑↑ (8,1 to 12.9 d)	<	↑↑ (14,9 to 21 d)	Design approach of aerobic and anoxic volumes (Reason B)
S_{NO}	↓ (39,7 to 39.3 mg/l)	>	↑ (37,4 to 38,6 mg/l)	SRT nitrification approach (Reason A)
Q_{INT}	↓ (91.870 to 90.788m^3/d)	>	↓ (84.756 to 82.745 m^3/d)	SRT nitrification approach (Reason A)
$W_{M,T}$	- (3.097 to 3.161 kg/d)	>	- (2.230 to 2.341 kg/d)	Design approach of the aerobic and anoxic volumes (Reason D)
V_{AER}	↑↑ (8.345 to 13.544 m^3)	>	↑↑ (5.576 to 9.403 m^3)	Design approach of aerobic and anoxic volumes/ SRT nitrification approach (Reasons A and B)
V_{ANOX}	↑ (2.847 to 3.300 m^3)	<	↑↑ (5.550 to 7.086 m^3)	Design approach of aerobic and anoxic volumes (Reason B and C)
V_{TOTAL}	↑↑ (11.192 to 16.844 m^3)	<	↑↑ (11.125 to 16.489 m^3)	Design approach of aerobic and anoxic volumes (Reason B)
Q_{AIR}	- (4.492 to 4.420 kg/d as O_2)	<	↓ (5.022 to 4.857 kg/d as O_2)	Design approach of aerobic and anoxic volumes (Reason D)

3.5. Discussion

The proposed methodology to analyze and compare design guidelines has several advantages in the understanding of any wastewater treatment plant process. Firstly, it deepens the knowledge of the design guidelines identifying the principal characteristics and differences. Secondly, it allows the possibility to study simultaneously the design variable responses in a specific (one sample) or multiple (multiple samples) scenarios for multiple design guidelines by analysis of response surfaces. Thirdly, the scenario analysis enables to answer questions such *as what would happen if*- evaluating the effect of changing pre-defined conditions in multiple design guidelines.

The results presented in this case study for the analysis and comparison of the two design guidelines selected (Metcalf & Eddy and Grady guidelines) for the modified Ludzack Ettinger (MLE) configuration, opens the door to several discussions:

From the analysis qualitative is shown to the designers, regulators, operators, and plant owners which are the *principal characteristics and differences* of the designs, to then providing *useful information* of their consequences in the tank volumes and pumping sizing design by a quantitative and stochastic analysis comparison. In the presented case study, the principal characteristics and differences of the design guidelines are focused in the calculation of sludge retention time and in the procedure used to estimate the fraction of aerobic and anoxic volumes. The results reflects the effects to Metcalf & Eddy design does not account the simultaneous combination of both anoxic and aerobic process, considering that all organic matter is removed in the aerobic tank, estimating larger aerobic tanks and lower anoxic tanks. Another relevant point is the calculation of SRT, where the Metcalf & Eddy guideline always leads to higher values. It is not recommended to use this guideline in presence of low DO concentrations (0.5 - 1 mg/l) and ammonia-N effluent requirements (0,5 – 1.5 mg/l): The DO term in the Monod equation to calculate the SRT is so sensitive to these ranges, leading to very high and non-realistic SRTs and aerobic tank volumes (over 15.000 m^3).

The analysis brought to light the existing differences in the dimensions and distribution of tanks and pumping sizing between the different guidelines, which can provide useful information in terms of constructions and operating costs. For this reason, a thorough analysis balancing construction costs, aeration costs and costs of possible effluent violations would be strongly encouraged in order to optimize economically the plant designing.

Finally, note that one of the purposes of this study is to share, with the different parties involved in the design steps, knowledge regarding how should be used these guidelines knowing their limitations. In this sense, using the results and the observations done in this study, one methodology can be identified as better than the other one to ensure a better practice of the designing. About the design results (tank and pumping sizing values), the same conclusion is not yet possible due to a lack of data on real WWTP. For example, in this case study, the Grady guideline methodology used for tank volumes estimation seems to be better than Metcalf & Eddy guideline methodology because the latter does not take care of the simultaneous organic matter removal in the designing of both zones (aerobic and anoxic tanks). However, it is not possible to know which guideline gives the most appropriate design results yet because the number of simulations (1000) run is much higher than the number of available WWTP data to cover the entire initial conditions (influent fractions, safety factors, operational conditions, and effluent requirements).

4. BUDGET SUMMARY

The total budget for the final project, which is broken down in the following **Table 10**, amounting to a total of **5.484,96 €**

Table 10. Budget Breakdown.

Equipment	***Unit price (€/h)***	***Hours spent***	***Total price (€)***
Computer depreciation	4,00	699,00	27,96
Software license depreciation	5,00	3.000,00	150,00
Printing/photocopying		20,00	20,00
		TOTAL COST EQUIPMENT	**197,96 €**
Labor	***Unit price (€/h)***	***Hours spent***	***Total price(€)***
Researcher staff			
Meetings: Supervision of the work	35,00	20,00	700,00
Review of results and writing	35,00	5,00	175,00
Student			
Process of information gathering	0,00	60,00	0,00
Development tool	12,00	300,00	3.600,00
Analysis and comparison of the selected case study	12,00	25,00	300,00
Writting of the project	8,00	64,00	512,00
		TOTAL COST OF LABOR	**5.287,00 €**
		TOTAL COST	**5.484,96 €**

5. CONCLUSIONS

The work conducted in this project contributes to the understanding of wastewater treatment plant design guidelines and provides a useful tool to analyze and compare different design approaches.

First, it was possible to deepen the understanding of the two guidelines selected (Metcalf & Eddy and Grady). Differences were found in the calculation of sludge retention time and in the procedure used to estimate the fraction of aerobic and anoxic volumes.

Second, we contributed to the development of an automatic tool to allow simultaneous analysis and comparison of multiple WWTP designs. With the tool it is possible to evaluate variation of the different design variables as function of a set of ranges of initial assumption representing lack of knowledge, engineering choices, regulator choices on effluent limits or preferences of the future operator. Additionally, the tool allows the process designer to learn and deduce general properties of multiple design guidelineS selected.

Thirdly, an analysis and comparison of two design guidelines was conducted by using the developed tool. The results show the consequence from the differences in the calculation of the sludge residence time and in the procedure to estimate the fraction of aerobic and anoxic volumes. In the calculation of the SRT, the Metcalf & Eddy approach is strictly sensitive to low DO concentrations (0.5 - 1 mg/l) and ammonia-N effluent requirements (0,5 – 1.5 mg/l), leading to high and non-realistic SRTs and aerobic tank volumes. In the estimation of the aerobic and anoxic tank volumes, Metcalf & Eddy design does not account the simultaneous organic matter removal in the designing of the anoxic and aerobic zones, leading to oversized aerobic reactors (75% of the required total volume). The Grady design considers that the majority of organic matter is consumed first in the anoxic zone, giving equilibrate distributions, around the 50 % in each zone tank. Thus, Grady design will always give lower aerobic tank volume, higher anoxic volume and lower total tanks volumes than Metcalf & Eddy guideline.

Finally, the scenario analysis shows the effects of not applying safety factors, which leads to a substantial decrease in the tanks and pumping sizing. On the other hand, the effects due to a decrease the temperature leads to a variation in the distribution of the volumes and a significantly increase of these, where the percentage of aerobic volume increases up to the 81.4 % in Metcalf & Eddy design and up to 56.6 % in Grady design.

Girona, 14th of june of 2011.

Ignasi Aymerich Blazquez

6. BIBLIOGRAPHY

[1] COROMINAS LL., FLORES-ALSINA X., MUSCHALLA D., NEWMANN M.B. AND VANROLLEGHEM P.A., Verification of WWTP Design guidelines with Activated Sludge Process Models. 2010. Publication: WEFTEC 2010, 2-6 October (2010), New Orleans, U.S.A.

[2] FLORES-ALSINA X., COROMINAS LL., MUSCHALLA D., NEUMANN M.B. AND VANROLLEGHEM P.A., How do Initial Design Assumptions Determine Plant Sizing? Assessing Activated Sludge Process Design using Monte-Carlo Simulation and Global Sensitivity Analysis. 2010. Publication: IWA World Water Congress and Exhibition, 19-24 September (2010), Montréal, Canada.

[3] GRADY L., DAIGGER G., LIM H., Biological Wastewater Treatment. Marcel Dekker. 2nd Edition, revised and expanded. New York (1999).

[4] HENZE M., GUJER W., MINO T. AND VAN LOOSDRECHT M.C.M., Activated Sludge Models ASM1, ASM2, ASM2D and ASM3. IWA Publishing, Scientific and technical report nº9 (IAWQ). London (2000).

[5] METCALF & EDDY INC., TCHOBANOGLOUS G., BURTON FRANKLIN L., Wastewater Engineering: Treatment and Reuse. McGraw-Hill series in civil and environmental engineering. 4th Edition. Boston (2003).

7. GLOSSARY

ASM1	Activated Sludge Model No 1
BOD_5	Biological Oxygen Demand consumed in five days
BSM1	Benchmark Simulation Model No 1
COD_{TO}	Chemical Oxygen Demand [g COD m^{-3}]
DO	Dissolve Oxygen [g O_2 m^{-3}]
f_S_{NH}	Ammonia-N fraction [-]
f_S_B	Soluble (Readily) biodegradable organics fraction [-]
f_S_{ND}	Soluble biodegradable organic nitrogen fraction [-]
f_S_U	Soluble inert organics fraction [-]
f_X_{ND}	Particulate biodegradable organic nitrogen fraction [-]
f_X_B	Particulate (Slowly) biodegrable organics fraction [-]
f_X_{OHO}	Heterotrophic biomass fraction [-]
$f\_X_{U,inf}$	Particulate inert organics fraction [-]
IWA	International Water Association
LHS	Latin hypercube sampling

MC	Monte Carlo
MLE	Modified Ludzack Ettinger
MLSS	Mixed liquor suspended solids [g TSS m^{-3}]
N	Nitrogen
Q	Influent flow rate [m^3 day-1]
Q1	First quartile
Q3	Third quartile
Q_{AIR}	Aeration flow rate [kg O_2 day-1]
Q_{INTR}	Internal recycle flow rate [m^3 day-1]
rbCOD	Readily biodegradable organics [g COD m^{-3}]
S	Scenario
S_B	Soluble (Readily) biodegradable organics [g COD m^{-3}]
sBOD	Soluble BOD_5 [g COD m^{-3}]
sCOD	Soluble COD [g COD m^{-3}]
SDNR	Specific denitrification rates
SF_{AER}	Safety factor in AER [-]

S_{NHX}	Effluent ammonium [g N m^{-3}]
S_{NOX}	Nitrate produced in the aerobic zone [g N m^{-3}]
S_{NOX}	Effluent nitrate [g N m^{-3}]
S_{O2}	Dissolved oxygen concentration in AER [g (-COD) m^{-3}]
SRT	Sludge retention time [days]
SRT_{AER}	Sludge retention time in the aerobic zone [days]
SRT_{ANOX}	Sludge retention time in the anoxic zone [days]
S_U	Soluble inert organics [g COD m^{-3}]
TKN	Total Kjeldahl Nitrogen [g N m^{-3}]
TSS	Total suspended solids [g TSS m-3]
V_{AER}	Aerobic Volume [m3]
V_{ANOX}	Anoxic Volume [m3]
VSS	Volatile suspended solids [g VSS m-3]
W_{MT}	Sludge production [kg d]
WWTP	Wastewater Treatment Plant
X_B	Particulate (Slowly) biodegrable organics [g COD m-3]

X_{OHO}	Heterotrophic biomass [g COD m-3]
$X_{u,inf}$	Particulate inert organics [g COD m-3]
[A]	Initial Assumptions
[X]	Design variables