EPS
Escola Politècnica
UdG Superior

Projecte/Treball Fi de Carrera

Estudi: Enginyeria Industrial. Pla 2002

Títol:
A tool for optimum design of Waste Water Treatment Plants under uncertainty.

Document: Memòria

Alumne: Josep Altimir i Puigdemont

Director/Tutor: Lluís Corominas / Narcís Gascons
Departament: Eng. Mecànica i de la Construcció Industrial
Àrea: Enginyeria Mecànica

Convocatòria (mes/any): Setembre 2012

Index

1 INTRODUCTION

1.1 Background

Human manipulation of the environment and especially the non-sustainable exploitation of natural resources (*Figure 1*) have led to unbalances in the natural ecosystems, which affects the soil, the water and the 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.

Figure 1. National Park of Fjord of Saguenay (Québec)

Nowadays, an important effort is being made to conserve the natural resources and to make a responsible use of water. Wastewater is understood as the flow of used water discharged from households, businesses, industries, commercial activities and institutions, which is conducted to treatment plants through the urban sewer system. The term “domestic wastewater” is used to talk about the flows discharged principally from households and residential sources generated by such activities as food preparation, laundry, cleaning and personal hygiene. Most of the wastewater is properly treated in wastewater treatment plants before discharging to the receiving waters (rivers, lakes, sea). Pollution caused by untreated water will have a negative 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 natural water resources, such as rivers, lakes or reservoirs.

A wastewater treatment plant (WWTP in the following) is an installation that reproduces the biochemical processes that naturally occur in rivers in a concentrated manner (*Figure 2*). Wastewater treatment plant facilities are designed and constructed to conduct these processes in an efficient way. They facilitate the organic matter biodegradation and removal of nitrogenous compounds by fostering microorganism activity under controlled operating conditions.

Figure 2. Aerial picture of a Wastewater treatment plant.

Currently, the WWTP design is based on the use of standard guidelines such as Metcalf & Eddy (Tchobanoglous et al., 2003), ATV-DVWK (ATV, 2000), Grady, Ten State Standards (2004) and HAS principles. These guidelines can be seen as steady state models where the design variables (total volume, secondary settler dimensions, oxygen requirements, etc.) are obtained from mass balances of COD, nitrogen and phosphorous (Alex et al., 2007). The limitation of these methods is twofold: they do not consider the dynamics of the system; the uncertainty about the plant performance is tackled by the use of safety factors which represent the lack of knowledge about the influent load and its composition, the biochemical behaviour of the system, possible hydraulic short-circuits, etc. The effect of these safety factors is not clear and may result into oversized designs (leading to higher operating and construction costs) or undersized designs (leading to lower effluent quality or limiting future capacity of the plant).

Umbrella-DOUT (Umbrella – Design and Operation Uncertainty Task Group) is a net of six interconnected projects in which Université Laval (Québec) is working in collaboration with Canadian and USA consultancies as well as funding from the Canadian government and international water organizations. The overall objective of U-DOUT is to analyse how uncertainty is being tackled in Wastewater Treatment Plants management, and how we can incorporate the uncertainty concepts into the design and operation of WWTPs. Figure 3 presents the U-DOUT projects and their time schedule:

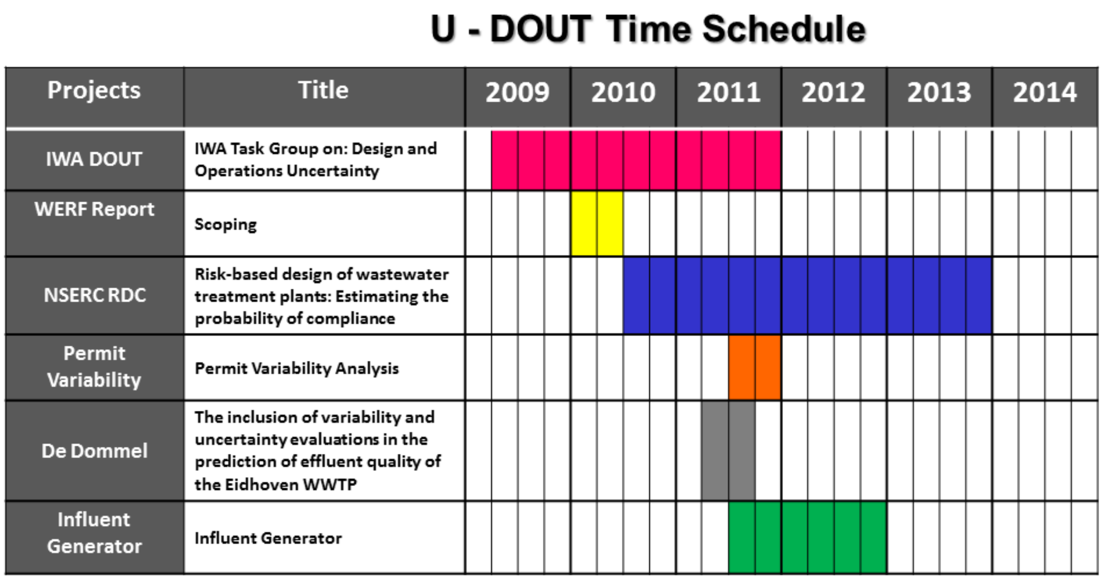

Figure 3. Umbrella-DOUT (U-DOUT) Time Schedule.

The three projects of the U-DOUT that are most clearly related to this project are: the IWA DOUT Task Group, the NSERC RDC and the Influent Generator. The IWA Specialist Task Group intends to bring together the collective knowledge of engineers, academics and plant owners, from several countries and continents. The final objective is to deliver a Scientific and Technical Report that recollects the state of the art and current practise about design and operations under uncertainty; and projects the most appropriate future directions. NSERC RDC aims at developing a general protocol that incorporates uncertainty evaluations in model-based plant design and optimization. The project also proposes to analyse the design guidelines and their reserve capacity; as well as evaluating the result of already built WWTP by post project audits. The Influent Generator project intends to provide a mathematical tool for influent generation able to catch the properties of the catchment area (population equivalents; industrial discharges; type and length of the sewer system; etc.) as well as reproducing the variability of the profiles observed at the entrance of a given WWTP. Dr. Marc B. Neumann, Dr. Cristina Martín and Prof. Peter Vanrolleghem participate in all the projects under the U-DOUT initiative, coordinating some of them. Prof. Peter Vanrolleghem holds the Canada Research Chair on Water Quality Modelling, at Université Laval in Québec (Canada), around which the model*EAU* research group has been founded (http://modeleau.fsg.ulaval.ca/). 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 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 U-DOUT framework being at the same time the result of a fruitful collaboration between model*EAU* and ICRA. Thanks to the PROMETEU program of the *Univesitat de Girona* a stage of six months at model*EAU* was conducted during the second semester of the 2011/2012 season. The work at model*EAU* was directly supervised by Cristina Martín (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).

1.2 Objectives

The main objective of this project is to present a new prototype tool for WWTP design using dynamic mechanistic models and quantifying the associated uncertainty. The main objective will be pursued together with two secondary objectives:

- Demonstrating that dynamic mechanistic models simulation can be used to design WWTPs.
- Using uncertainty analysis to assess the effect of the lack of knowledge during the design procedure (about the settling mechanisms, biochemical processes, etc.).
- Applying the design prototype tool to re-design a benchmarked WWTP

By achieving these objectives, engineers will have a tool that incorporates uncertainty during the design procedure. Incorporating uncertainty will help in the selection of the best design configuration for a given design problem.

1.3 Specifications and scope

The scope of this project is to propose a prototype tool for WWTP design under uncertainty. The tool is addressed to engineers to improve their understanding of the system and to obtain better designs. This project has the following boundaries:

- The prototype tool is aimed at the designing activated sludge reactors (for the removal of ammonium and organic matter). It does not include the design of the whole WWTP (e.g. pre-treatment, primary treatment, sludge treatment).
- The tool combines dynamic mechanistic models with statistical methods to account for uncertainty.
- The uncertainty analysis applied in this project is only illustrative as it accounts for the most relevant sources of uncertainty during process design (but not all). This analysis should be tailored to each particular case study.
- The project presents a prototype tool that is the first step towards a general methodology for a WWTP design under uncertainty.

The benefits of the new mathematical tool will be demonstrated on the Benchmark Simulation Plant nº1 (a standardized plant layout widely used in the scientific community).

2 MATERIALS AND METHODS

This section gives a general overview of the methodology used in this project for the analysis of the different WWTP proposed designs. The next sections provide: i) a brief description of the general methodology, ii) definition of the simulation platform, and finally iii) the evaluation of the designs in the simulation platform.

2.1 General methodology of the prototype tool

2.1.1 Using a dynamic mechanistic model

Figure 4 explains the use of dynamic simulation models for design**.** First, the initial assumptions of the design are defined (influent, model parameters and design variables) which will be the inputs of the system. Then, a simulation of the WWTP mathematical model is run using these initial assumptions. The outcome of the model is a prediction of the WWTP effluent concentrations (i.e. ammonia, nitrate, total suspended solids).

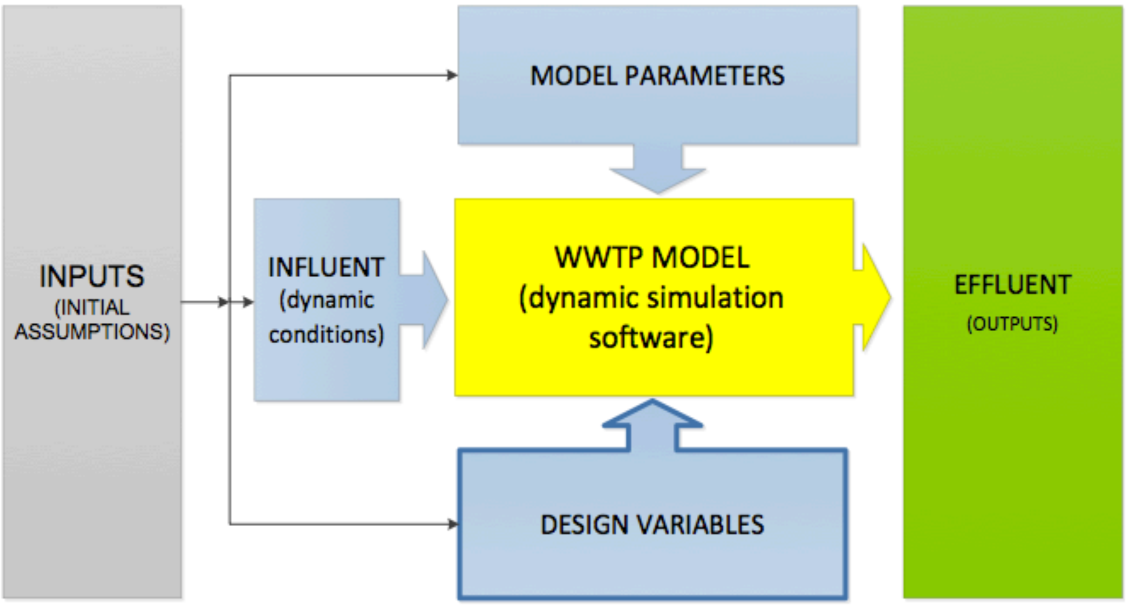

Figure 4. Design methodology for WWTP, observing the initial assumptions (influent flow, operational conditions and design variables) assumed as inputs, and the Effluent flow obtained (outputs) by dynamic simulation of a WWTP model.

2.1.2 Evaluation of Designs under Uncertainty

In order to design under uncertainty, different combinations of initial assumptions can be generated and then introduced into the WWTP model. Therefore, multiple predictions can be obtained. Each of these predictions corresponds to a design of the system. Afterwards, they are evaluated and a selection procedure is conducted.

The assessment of a certain design is basically performed by completing two simulation loops (*Figure 5*):

- -The inner loop performs simulations applying uncertainty both to the model parameters and the design variables. The inner loop is also called Monte Carlo loop (MC).
- The outer loop performs simulations trying different combinations of design variables exploring a wide range of the design space.

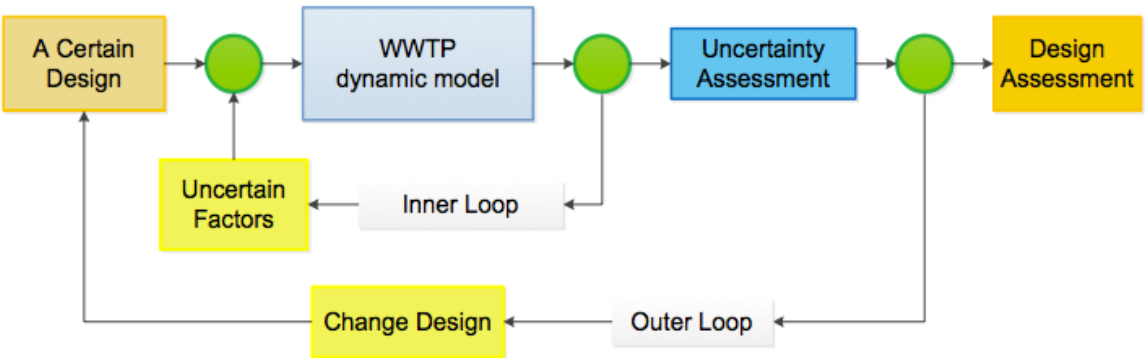

Figure 5. Simulation scheme followed for design assessment under uncertainty.

For a certain design, the inner loop evaluates the effect of the uncertain factors on the water quality criteria in the effluent. The result is represented by means of a histogram for each effluent criteria (Graph 1, *Figure 6)*: TSS maximum, TSS average, NH_4 maximum, NH_4 average, TN maximum, TN average, NO_3 maximum and NO_3 average. This operation is repeated over a sufficiently large selection of model designs (outer loops) and all the histograms obtained are summarized by their percentile distribution, represented by Graph 2 (*Figure 6*). It is also important to note, that all the values in Graph 2 (*Figure 6*) are represented in decreasing order (from larger to lower values).

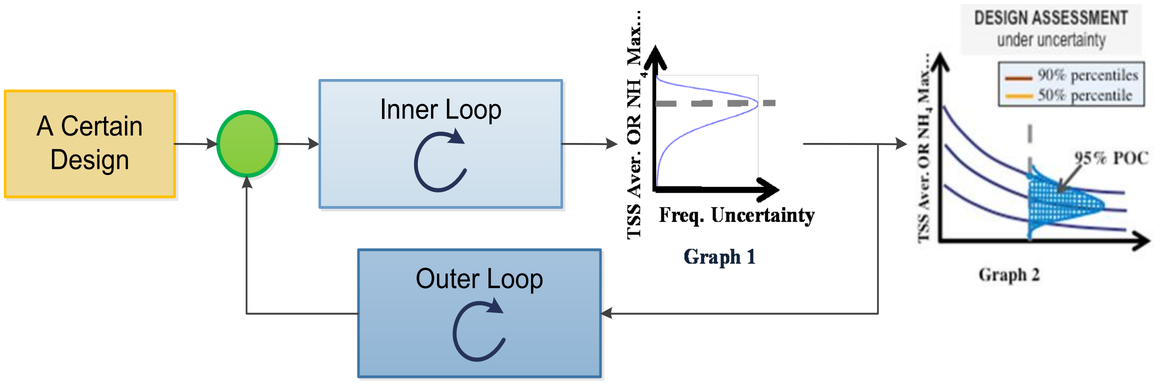

Figure 6. Simulation scheme followed for design assessment under uncertainty

In the next sections the numerical techniques and mathematical methods required to run the above methods for the evaluation of designs are presented.

2.1.2.1 Monte Carlo (MC) Loop

The Monte Carlo technique is the numerical method followed to propagate the uncertainty defined in the uncertain input factors through the system. Monte Carlo simulations make reference to random numbers, the name being derived from the roulette wheels in Monte Carlo casinos. The method, which has been used in a very wide variety of contexts, consists of simulating the model several times while randomly sampling the input parameters to obtain several measures of the system response. Statistical analysis of the model responses provides a more realistic understanding of the system behaviour. McIntyre et al. (2002)made a review of the Monte Carlo based methods for uncertainty estimation and propagation analysis in environmental models. Other application examples can be found in Benedetti et al. (2006) or Flores-Alsina et al. (2008; 2009).

According to Rousseau et al. (2001) and Willems and Berlamont(2002), if the model input variables are randomly generated in accordance with their inherent uncertainty, the Monte Carlo technique provides an assessment of uncertainty in the model responses. The method naturally handles non-linear models and takes into account partial and perfect correlation effects between input parameters and model responses without any extra complication. Moreover, Papadopoulos and Yeung(2001) demonstrated that the Monte Carlo simulation method is fully compatible with conventional uncertainty estimation methods. The only drawback of the method is the large number of model runs usually required to correctly infer the natural output variability.

2.1.2.2 Latin Hypercube Sampling (LHS)

Latin hypercube sampling (LHS) is a statistical method for generating a distribution of plausible collections of parameter values from a multidimensional probability distribution function. The sampling method is often applied in uncertainty analysis. McKay first described the technique in 1979. It was further elaborated by Ronald L. Iman and others in 1981. In the context of statistical sampling, a square grid containing sample positions is a Latin square if (and only if) there is only one sample in each row and each column. A Latin hypercube is the generalisation of this concept to an arbitrary number of dimensions, whereby each sample is the only one in each axis-aligned hyper plane containing it.

When sampling a function of variables, the range of each variable is divided into equally probable intervals. Sample points are then placed to satisfy the Latin hypercube requirements. Note that this forces the number of divisions to be equal for each variable. Also note that this sampling scheme does not require more samples for more dimensions (variables); this independence is one of the main advantages of this sampling scheme. Another advantage is that random samples can be taken one at a time, remembering which samples were taken so far.

2.2 Simulation Platform

The objective of this section is to present the Benchmark Simulation Model No.1 (BSM1), which is the case study used in this project to test the prototype methodology. The BSM1 was proposed as a tool for evaluating activated sludge wastewater control strategies (Copp, 2001). The Activated Sludge Unit is modelled using the activated sludge model no.1 (ASM1, Henze et al., 2000). The Settling unit is modelled using the Takács settling model (Takács et al., 1991).

2.2.1 Configuration of Benchmark Simulation Model No.1

The BSM1 is a simulation environment ideated to test different control strategies (*Figure 7*). The BSM1 has been largely used in the scientific context as standard predenitrifcation and nitrification systems to test different operational and control strategies (Copp, 2001); to assess new modelling approaches or even to define new design methods. For each of these items, compromises were pursued to combine plainness with realism and accepted standards.

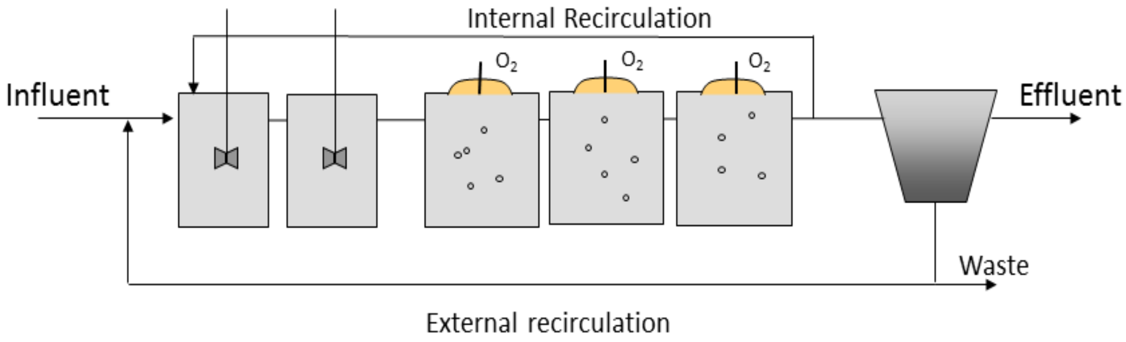

Figure 7. Benchmark Simulation Model No.1 plant configuration.

2.2.2 Biochemical Model

The benchmark plant is composed of a five-compartment activated sludge reactor. The first two tanks are anoxic and fulfil the *denitrification process*, while the second three tanks are aerobic and fulfil the *nitrification process* (*Figure 8)*.

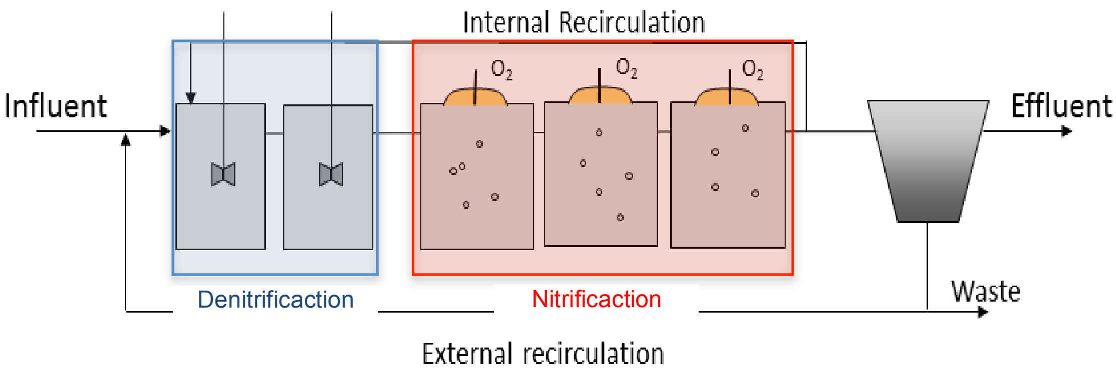

Figure 8. Benchmark Simulation Model nº1. Denitrification / Nitrification parts.

Another important characteristic of a plant is the *Sludge Retention Time* (SRT) and the *Hydraulic Retention Time* (HRT). The *Sludge Retention Time* is the average time the activated sludge solids are in the system. The SRT is an important design and operational parameter for the activated sludge process and is usually expressed in days. The HRT is a measure of the average of time that a soluble compound remains in a bioreactor. The HRT is calculated as the volume of the aeration tank divided by the influent flow rate. In this specific experiment the SRT is 10 days and the HRT 15 hours. For further information on BSM1 the reader is referred to the IWA Task Group on Benchmarking of Control Strategies for WWTPs (http://www.benchmarkwwtp.org/) and Copp (2001).

2.2.2.1 Denitrification and nitrification processes

Denitrification is the biological process in which the heterotrophic organisms convert nitrate to nitrogen gas by using organic matter as electron donor and nitrates as electron acceptor. This process only operates in the absence of oxygen (*equation 1*):

$$6\,NO_3^- + 5\,CH_3OH \;\rightarrow\; 3\,N_2 + 5\,CO_2 + 7H_2O + 6\,OH' \qquad \textit{(eq. 1)}$$

Nitrification is the biological process conducted by autotrophic microorganisms that obtain energy from the oxidation of ammonia into nitrate (*eq. 2).*The nitrification reaction generates nitrate (*NO*$_3$) that is necessary for denitrification. Thus, Internal Recirculation is needed to eliminate nitrates and ammonia (*equation 2)*:

$$NH_4^+ + 1.5\,O_2^- \;\rightarrow\; 2\,H^+ + 2\,H_2O + NO_2^- \qquad \textit{(eq.2)}$$

$$NO_2^- + 0.5\,O_2^- \;\rightarrow\; NO_3^-$$

The plant combines nitrification and predenitrification in a configuration that is commonly used for achieving biological nitrogen removal in full-scale plants. As denitrification requires a source of organic matter, the BSM1 configuration places the anoxic zone at the beginning due to the organic matter available from wastewater. The nitrates, product of the nitrification, are recirculated upstream (internal recirculation) in order to be used by the heterotrophic bacteria for denitrification. One should think the aerobic tanks before the anoxic ones, so that the internal recirculation would not be necessary. However, in such a case the organic material would be biodegraded in aerobic conditions (preferred by the heterotrophic bacteria) and the nitrates would not be eliminated.

The activated sludge is thickened in the settler so that the clarified supernatant flows to the effluent. Some part of the thickened sludge is recirculated upstream (external recirculation) so that a high concentration of biomass is kept in the system. The rest is the waste sludge, which will be treated in the sludge line.

The settling unit is in charge of separating the solids from the water. The separation of solids from water by gravity sedimentation is one of the most important physical processes in a WWTP. By design, Activated Sludge Plants transform soluble organic matter into biomass; the effective operation of the process requires that the biomass to be removed from the liquid stream (in the secondary settler) prior to being discharged in the receiving waters. Part of the biomass is wasted, while a large fraction is returned to the biological reactor (*External Recirculation*) to maintain the appropriate substrate-to-biomass ratio.

Summarizing, the water to treat will be entering the system as *“Influent”* and will be headed to the *Anoxic tanks*. After the denitrification process, the nitrification process starts in the *Aerobic tanks*. A mixed liquor recirculation, *Internal Recirculation* (Q_{INT}), will transfer the nitrate-N generated in the aerobic zone back to the initial anoxic zone where it is required. Finally, the treated water will be headed to the Settling Unit. The secondary settler follows the activated sludge reactor.

2.2.2.2 Activated Sludge Model nº1 (ASM1)

The Activated Sludge Model nº1 (ASM1) was developed in 1987 (Henze et al., 1987) in order to reach a consensus concerning the simplest mathematical model having the capability of realistically predicting the performance of single-sludge systems carrying out the decay of organic matter, nitrification and denitrification.

Organic matter in wastewater may be subdivided into a number of categories (McKinney and Ooten, 1969; Dold et al., 1980) based on biodegradability (*Figure 9*).

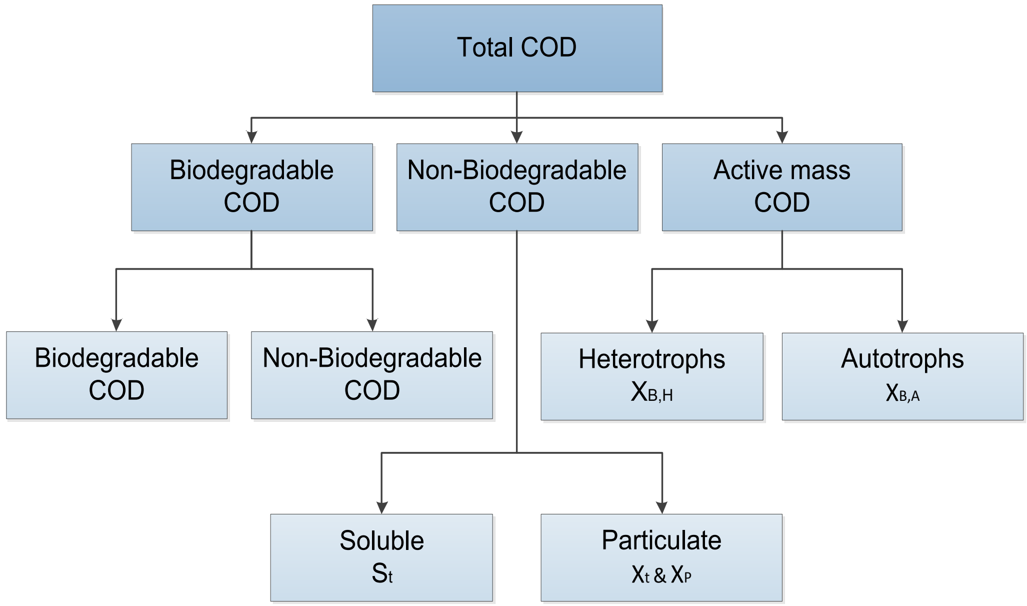

Figure 9. COD components in Activated Sludge Model nº1 (ASM1)

Nitrogenous matter in a wastewater can be divided into two categories: non-biodegradable and biodegradable, each one with further divisions (*Figure 10*).

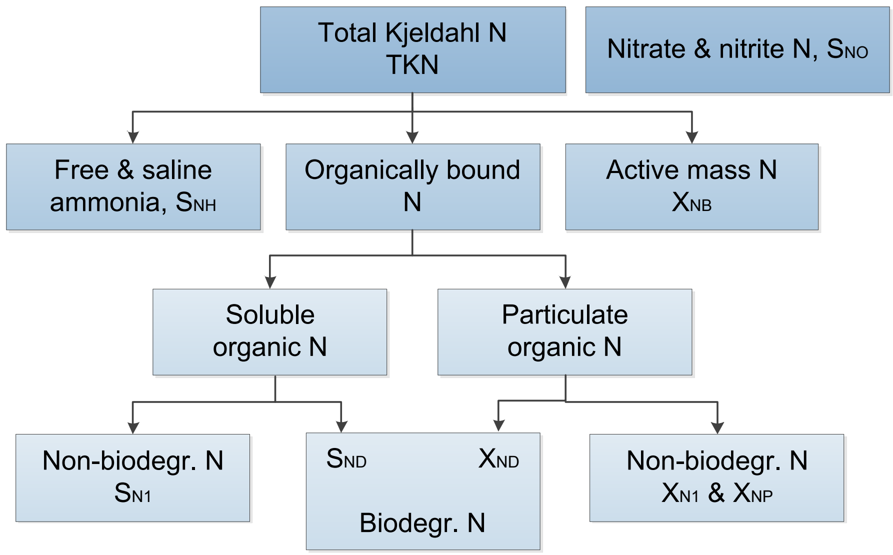

Figure 10. Nitrogen components in Activated Sludge Model nº1.

The ASM1 model describes the organic material biodegradation, the nitrification and denitrification processes by means of the following processes:

- Aerobic growth of heterotrophic biomass, $X_{B,H}$
- Anoxic growth of heterotrophic biomass (denitrification)
- Growth of autotrophic biomass, $X_{B,A}$ (nitrification)

- Decay of heterotrophic biomass
- Decay of autotrophic biomass
- Ammonification of soluble organic nitrogen
- Hydrolysis of entrapped organics
- Hydrolysis of entrapped organic nitrogen

The wastewater characteristics are featured by means of 13 components that are sufficient to describe the reactants and products of the above-mentioned transformations. These are:

- S_I: Soluble inorganic matter.
- S_S: Easily biodegradable organic matter.
- X_I: Particulate inert organic matter.
- X_S: Slowly biodegradable substrate.
- $X_{B,H}$: Active heterotrophic biomass.
- $X_{B,A}$: Active autotrophic biomass.
- X_D: Particulate products arising from biomass decay.
- S_O: Oxygen (negative COD).
- S_{NO}: Nitrate and nitrite nitrogen.
- S_{NH}: NH_4+NH_3 nitrogen.
- S_{ND}: Soluble biodegradable organic nitrogen.
- X_{ND}: Particulate biodegradable organic nitrogen.
- S_{ALK}: Alkalinity.

The stoichiometric matrix defines the mass of each component that disappears or appears at each biochemical reaction (see *Figure 11*). The process rate expresses the velocity at which the biochemical reaction takes place. Unfortunately, most of the parameters of the ASM1 model (K_{OH}, μ_A, b_H, b_A, etc.) have not been uniquely determined and their default values have some degree of uncertainty.

Component → *i* / *j* Process ↓	1 S_I	2 S_S	3 X_I	4 X_S	5 $X_{B,H}$	6 $X_{B,A}$	7 X_P	8 S_O	9 S_{NO}	10 S_{NH}	11 S_{ND}	12 X_{ND}	13 S_{ALK}	Process Rate, ρ_j [$ML^{-3}T^{-1}$]
1 Aerobic growth of heterotrophs		$-\frac{1}{Y_H}$			1			$-\frac{1-Y_H}{Y_H}$		$-i_{XB}$			$-\frac{i_{XB}}{14}$	$\hat{\mu}_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{S_O}{K_{O,H}+S_O}\right)X_{B,H}$
2 Anoxic growth of heterotrophs		$-\frac{1}{Y_H}$			1				$-\frac{1-Y_H}{2.86Y_H}$	$-i_{XB}$			$\frac{1-Y_H}{14\cdot 2.86Y_H}-\frac{i_{XB}}{14}$	$\hat{\mu}_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{K_{O,H}}{K_{O,H}+S_O}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\eta_g X_{B,H}$
3 Aerobic growth of autotrophs						1		$-\frac{4.57}{Y_A}+1$	$\frac{1}{Y_A}$	$-i_{XB}-\frac{1}{Y_A}$			$-\frac{i_{XB}}{14}-\frac{1}{7Y_A}$	$\hat{\mu}_A\left(\frac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_O}{K_{O,A}+S_O}\right)X_{B,A}$
4 'Decay' of heterotrophs				$1-f_P$	−1		f_P					$i_{XB}-f_P i_{XP}$		$b_H X_{B,H}$
5 'Decay' of autotrophs				$1-f_P$		−1	f_P					$i_{XB}-f_P i_{XP}$		$b_A X_{B,A}$
6 Ammonification of soluble organic nitrogen										1	−1		$\frac{1}{14}$	$k_a S_{ND} X_{B,H}$
7 'Hydrolysis' of entrapped organics		1		−1										$k_h\frac{X_S/X_{B,H}}{K_X+(X_S/X_{B,H})}\left[\left(\frac{S_O}{K_{O,H}+S_O}\right)+\eta_h\left(\frac{K_{O,H}}{K_{O,H}+S_O}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\right]X_{B,H}$
8 'Hydrolysis' of entrapped organic nitrogen											1	−1		$\rho_7(X_{ND}/X_S)$
Observed Conversion Rates [$ML^{-3}T^{-1}$]	$r_i=\sum_j v_{ij}\rho_j$									$r_i=\sum_j v_{ij}\rho_j$				
Stoichiometric Parameters: Heterotrophic yield: Y_H; Autotrophic yield: Y_A; Fraction of biomass yielding particulate products: f_P; Mass N/Mass COD in biomass: i_{XB}; Mass N/Mass COD in products from biomass: i_{XP}	Soluble inert organic matter [M(COD)L⁻³]	Readily biodegradable substrate [M(COD)L⁻³]	Particulate inert organic matter [M(COD)L⁻³]	Slowly biodegradable substrate [M(COD)L⁻³]	Active heterotrophic biomass [M(COD)L⁻³]	Active autotrophic biomass [M(COD)L⁻³]	Particulate products arising from biomass decay [M(COD)L⁻³]	Oxygen (negative COD) [M(−COD)L⁻³]	Nitrate and nitrite nitrogen [M(N)L⁻³]	NH_4^++NH_3 nitrogen [M(N)L⁻³]	Soluble biodegradable organic nitrogen [M(N)L⁻³]	Particulate biodegradable organic nitrogen [M(N)L⁻³]	Alkalinity – Molar units	Kinetic Parameters: Heterotrophic growth and decay: $\hat{\mu}_H$, K_S, $K_{O,H}$, K_{NO}, b_H; Autotrophic growth and decay: $\hat{\mu}_A$, K_{NH}, $K_{O,A}$, b_A; Correction factor for anoxic growth of heterotrophs: η_g; Ammonification: k_a; Hydrolysis: k_h, K_X; Correction factor for anoxic hydrolysis: η_h

Figure 11. Activated Sludge Model nº1 Matrix Format.

Concluding, ASM1 reproduces in a proper way the elimination of nitrogen and organic matter in biological reactors. However, it has some limitations:

- Biological phosphorus biological elimination is not reproduced.
- Experimentally there is no way to observe:
  - Any distinctions between the inert organic matter in the influent (X_t) and organims matter generated during the microorganisms' decay (X_P).
  - Ammonification kinetics.
  - Particulate and Soluble Organic Nitrogen (S_{ND} and X_{ND}).

Nevertheless, ASM1 is considered a solid and proper mathematical model for the scope and requirements of this project.

2.2.3 Takács Model

The settling unit modelled using the Takács settling model (Takács et al., 1991) is a non-reactive secondary settler subdivided into 10 layers. *Figure 12* represents a general scheme of the model. On the upper-left hand, the flow coming from the biochemical reactors (as input), and ion the upper-right hand, *Effluent* leaving the system (up zone to the right) and *Waste Flow* headed to the *External Recirculation* (down zone to the left) as outputs.

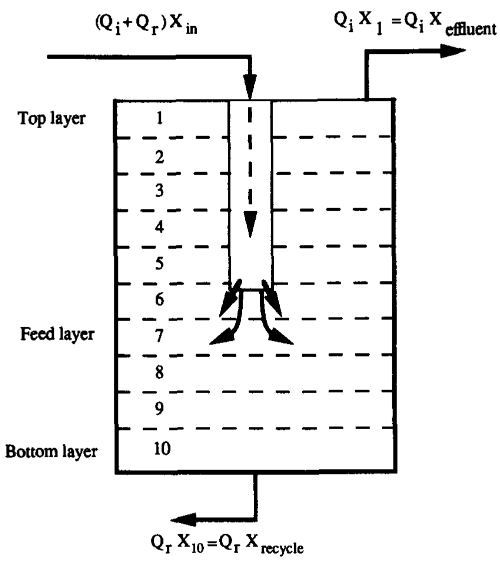

Figure 12. Layer Settler model. Takács Settling model.

The Takács model is based on the solids flux concept as the standard Vesilind model (Vesilind, 1968). The Takács model uses a double-exponential settling velocity function (*equation 3*):

$$V_{sj} = V_0 \cdot e^{-r_h \cdot X_j} - V_0 \cdot e^{-r_p \cdot X_j} \qquad \text{(eq. 3)}$$

$$0 \leq V_{S,j} \leq V_0{}'$$

V_{Sj} is the settling velocity in the layer.

V_O is the maximum settling velocity.

V_O' is the maximum practical settling velocity.

X_j is the TSS concentration in the layer.

2.2.4 Simulation Strategy

The model of the BSM1 layout was implemented and simulated in the WEST (www.mikebydhi.com) simulation platform. The simulations were performed for a constant temperature of 15 °C. To simulate the BSM1, the following strategy was used:

1) 150 days of steady-state simulation using constant dry weather influent load (steady-state load) to obtain a steady state.
2) 14 days of dynamic simulations using a dynamic dry weather influent load profile.
3) 14 days of dynamic simulations using a dynamic dry weather influent load profile. This last 14 days of dynamic simulations were considered for the plant performance evaluations.

Summarizing, the simulation is run for 178 days in total.

2.3 Evaluation of Designs in the simulation platform

2.3.1 Evaluation of Designs

For this first test of the prototype tool, 100 designs of the BSM1 platform are computed by considering random values of five design variables (*Table 1*): Total Volume, Waste flow rate, Recycle flow rate and Internal recirculation flow rate. Latin Hypercube Sampling (*explained in section 2.1.2.2*) was used to achieve a representative sample of the design space (*Table 1*).

Table 1 Default Values and Reasonable ranges of the design variables

	Unit	Default	Minimum	Maximum
Total Volume of Design (*TDV*)	m^3	6000	4600	7600
Aerobic Fraction of Design (*AFD*)	-	0.667	0.5	0.75
Waste flow rate of Design (*WFD*)	m^3day^{-1}	385	280	600
Recycle flow rate of Design (RFD)	m^3 day^{-1}	18446	14000	23000
Internal recirculation flow rate of Design (IRD)	m^3 day^{-1}	55338	40000	70000

2.3.2 Uncertainty Analysis

The uncertainty analysis evaluates the 16 uncertain factors (*Table 2)*, related to:

a) Hydraulics and mass-transfer (Sin et al., 2009 and Sin et al,. 2011)
b) Kinetics and Stoichiometry (Henze et al., 2000)
c) Influent fractionation (Henze et al., 2000)
d) Settling mechanism (Ramin et al., 2011)

The selection of the most relevant parameters has been based on previous results of a global sensitivity analysis (Sin et al., 2011; Ramin et al., 2011)

Table 2.Uncertainty of the most important design, biochemical and settling parameters.

Parameter	Unit	Default	Min	Max
Hydraulics and Mass-transfer				
Total Volume	m^3	*6000*	*0.9·TDV*	*1·TDV*
Aerobic fraction	-	*0.667*	*0.9·AFD*	*1·AFD*
Recycle flow rate	$m^3\ day^{-1}$	*18831*	*0.8·RFD*	*1·RFD*
Internal recirculation flow rate	$m^3\ day^{-1}$	*55338*	*0.75·IRD*	*1.25·IRD*
$K_La_{,Anox}$	day^{-1}		*0*	*10*
$K_La_{,Aer}$	day^{-1}		*180*	*360*
Kinetics and Stoichiometry				
K_{OH}	$g\ (-COD)\ m^{-3}$		*0.10*	*0.30*
K_{NH}	$gN\ m^{-3}$	*1.00*	*0.50*	*1.50*
K_{OA}	$gCOD\ m^{-3}$	*0.40*	*0.30*	*0.50*
b_A	day^{-1}	*0.05*	*0.04*	*0.06*
η_{hyd}	-		*0.60*	*1.00*
μ_A	day^{-1}	*0.50*	*0.48*	*0.53*
Influent fractionation				
i_{XB}	$gN\ (gCOD)^{-1}$	*0.08*	*0.04*	*0.12*
X_{ITSS}	$gTSS\ (gCOD)^{-1}$	*0.75*	*0.70*	*0.95*
Settling mechanism				
SVI	-	*100*	*75*	*105*
f_{NS}	-	*0.0023*	*0.001*	*0.005*
V_0	$m\ day^{-1}$	*474*	*427*	*521*

The uncertainty analysis has been performed by using Latin Hypercube sampling. It has been shown that 400 parameter sets were found sufficient to achieve the convergence of the results.

Once the 100 outer loops are finalized the histograms are generated (*Graph 1, Figure 6*), and the percentiles 5%, 50% and 95% obtained for each model design are used to create *Figure 13*.

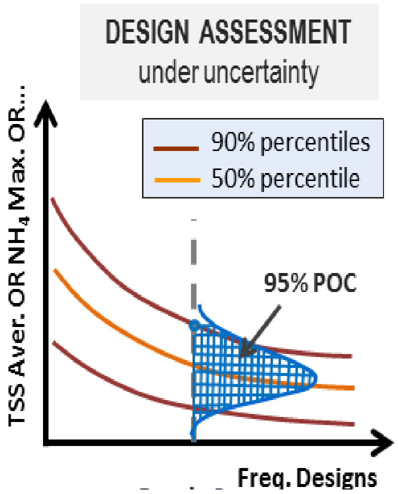

Figure 13. Graphics which represent the effluent criteria.

2.3.3 Probability of Compliance (POC)

The performance of the designs is assessed with respect to the maximum and average values of the ammonium (NH_4), nitrates (NO_3), total nitrogen (TN) and total suspended solids (TSS) concentrations in the effluent. The simulated results are compared with typical effluent requirements (*Table 3*).

Table 1. Effluent Requirements assumed to evaluate the plant designs under uncertainty

Variable	*Unit*	*Maximum*	*Average*
NH_4	mgN/l	6	3
NO_3	mgN/l	23	20
TN	mgN/l	25	23
TSS	mg/l	21	19

The probability of compliance (POC) is the probability that a certain design fulfils the effluent requirements given that all the uncertain factors are considered (*Table 3*). For each of the water quality criteria considered the histogram of the maximum and the average values are drawn (*Figure 14*) and by comparison with the effluent requirements (*Table 1*) the Probability Of Compliance (POC) has been computed.

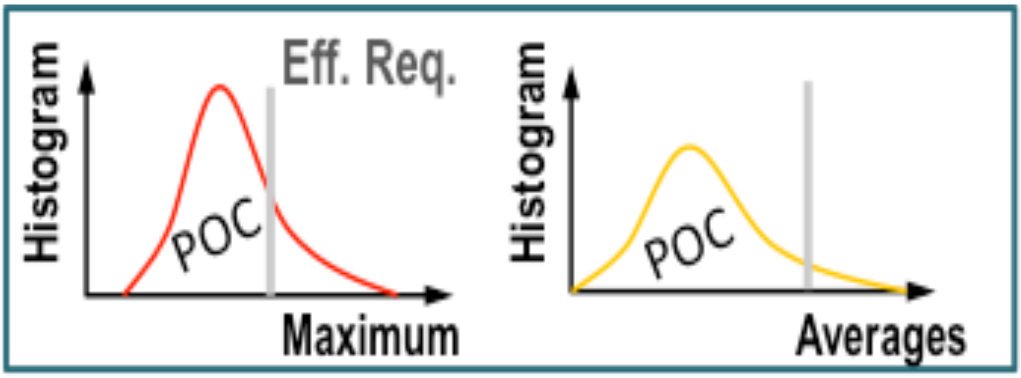

Figure 14. Representation of Probability of Compliance in standard histograms of effluent requirements.

Figure 14 represents two different histograms (Maximum and Average) for each of the four effluent criteria in this experiment (NH_4, NO_3, TN, TSS). The integral under the curve defined by the histogram and the vertical line of the effluent requirements is the POC. A certain design will then fulfil the Effluent requirements not always but with a probability defined by the POC.

2.3.4 Number of simulations and software

Overall, 40.000 (100x400) dynamic model simulations were performed using WEST2011 (www.mikebydhi.com). The uncertainty analysis tool of WEST 2011 has been very useful since the 40,000 simulations (*Figure 15*) could be performed by preparing only 100 simulation setups (corresponding to 100 different designs).

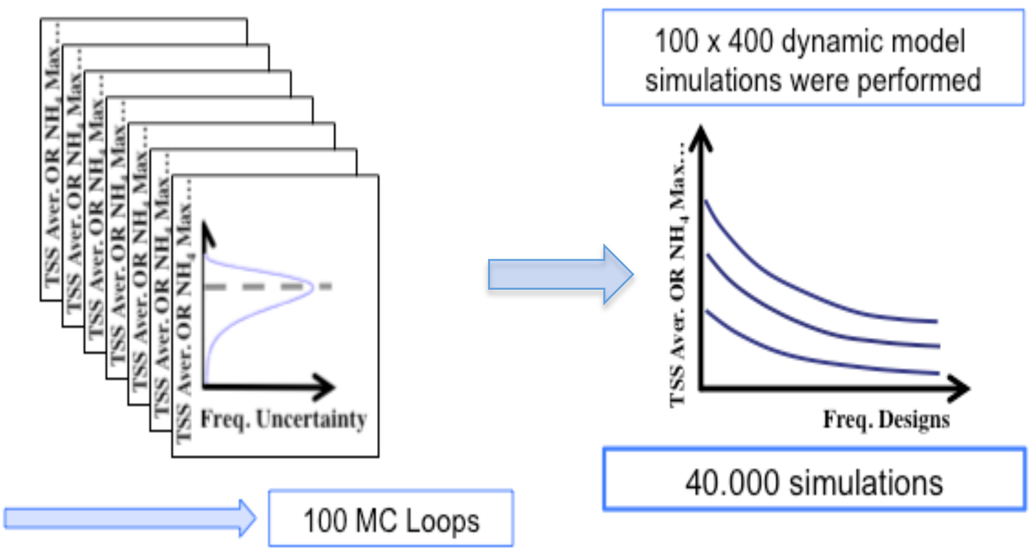

Figure 15. Summary of how the results are obtained after the simulation process. Find the histograms (from *Graph 1 in Figure 6*) in the left side of the figure and the Effluent Criteria Graph (*Figure 14*) on the right side.

3 RESULTS

This section gives the specific information about the results provided by the prototype design tool and how they are interpreted. The next section provides: i) a comparison of two representative WWTP designs, ii) a brief description of the uncertainty analysis and the probability of compliance of the two designs, iii) how the effluent criteria of an optimum design behave under uncertainty, iv) which is the relationship between the different output variables, and finally, v) which is the relationship between the most important design variables.

3.1 Time Series Analysis of two representative designs

This section analyses the dynamic simulation results of the two representative designs. For illustrative purposes, the concentration in the effluent is shown for the ammonium, nitrates, total nitrogen and total suspended solids of a working design (or a design that fulfils the effluent limits of *Table 1*) and a non-working design (a design that does not fulfil the effluent limits).

Figure 16 represents the time series of the NH_4, NO_3, TN and TSS in the effluent. The last 28 days of simulation of two proposed designs are shown: one in which the effluent ammonia and nitrate concentrations are below the predefined levels (Working Design or WD) and another one in which the predefined effluent concentrations are not achieved (Non-Working Design or NWD). The working design (WD) is represented in the left hand side of *Figure 16*, while non-working design (NWD) is represented on the right hand side.

The daily and weekly pattern is clearly observed, two concentration peaks per day (morning and afternoon) and a clearly distinguishable behaviour between weekdays and weekend days.

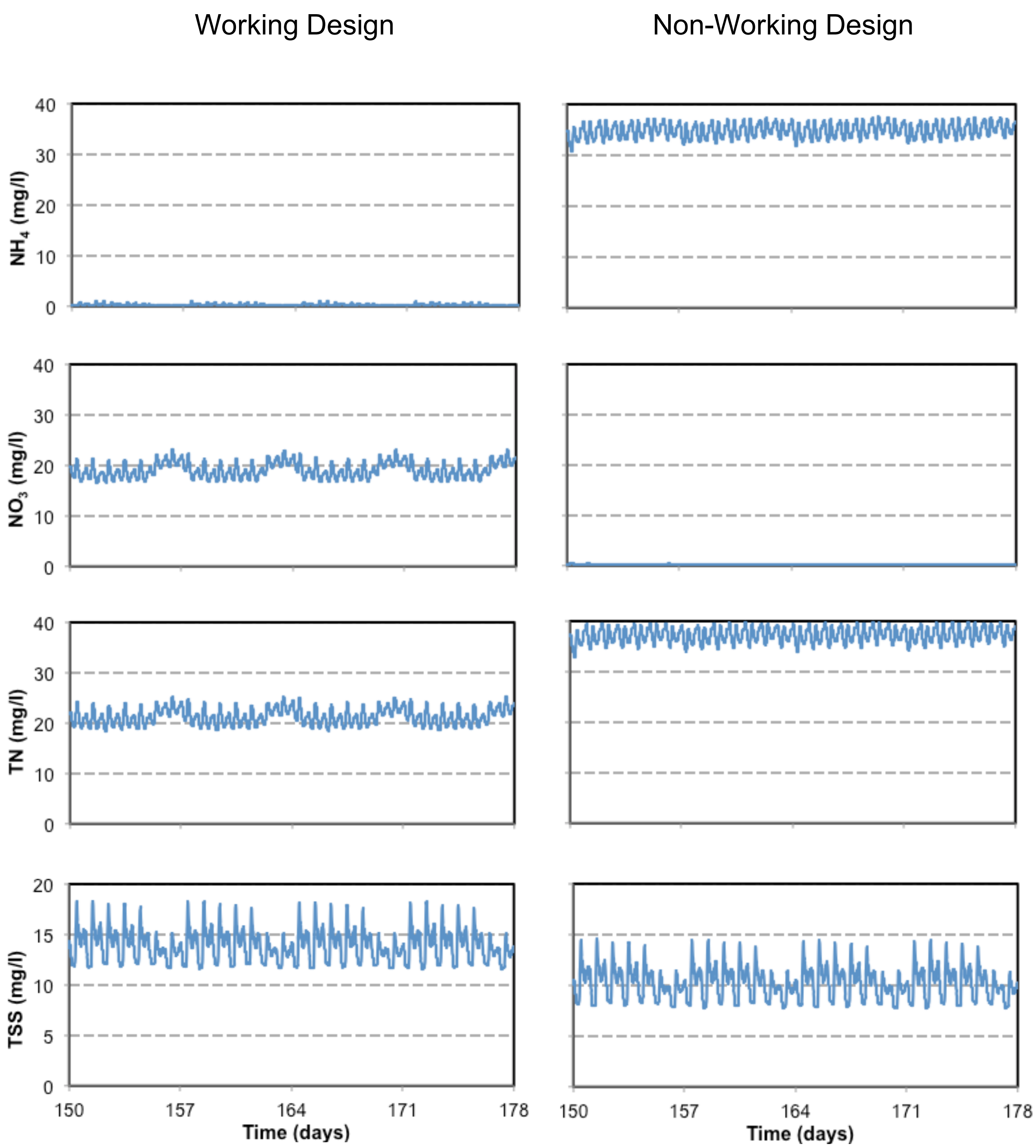

Figure 16. Time series results along the 28 days after the steady state reaching 14 days of dynamic simulation followed by 14 days of evaluation period.

The main difference between the two designs corresponds to the ammonium (NH_4) and nitrate (NO_3) concentrations. It is observed that the ammonium is very low in the WD (high nitrification rates are achieved) while it is extremely high in the NWD (it equals the influent concentration as no nitrification occurs). The nitrate concentration in the WD is around 20 mg/L (but still below the predefined effluent limits) because of the NO_3 generated during the nitrification process, while it is almost zero in the NWD. Overall, the TN concentration is lower in the WD proving that there is better nitrogen removal for WD. Finally, the concentration of the total suspended solids is higher in the WD than in the NWD (but still below the predefined limits). The increase of biological activity in the WD (higher nitrification and denitrification rates) generates more biomass and the total solids concentration in the reactor increases. This has an influence on the total solids also in the effluent of the system after settling.

Although not all concentrations are lower in the WD than in the NWD, the water quality in the effluent is considerably better in the WD plant:

- Ammonium (toxic for aquatic life) has nearly disappeared.
- Nitrates are nutrients so they are not so harmful; although they can promote eutrophication.
- Total nitrogen has decreased.
- The increase of total suspended solids is very low.

3.2 Uncertainty Analysis of two representative designs

This section analyses the results of the uncertainty analysis on the previously presented WD and NWD (*section 3.1.*).

Taking into account the same two designs, the effect of the uncertainty on them has been compared. For each design an uncertainty analysis on the uncertain factors has been performed (*section 2.1.2.*) by launching a set of 400 simulations.

Find in *Table 4* the analysis of uncertainty according to the standard deviation and the mean values of the results. The same results are represented in *Figure 17* as well as histograms. In *Figure 17*, one can find the histograms of NH_4, NO_3, TN and TSS average values in the effluent. Obviously, the mean values of histograms are around the mean values already observed in *Figure 16*. The histograms denote that the uncertainties of the system lead to quite high variability of the average concentrations in the effluent. Although not presented, the analysis of the histograms of the maximum values shows similar results.

Table 2.Standard Deviations for Uncertainty Analysis of two different designs, WD and NWD.

	Standard Deviation		***Means***	
	WD	*NWD*	*WD*	*NWD*
NH_4	0.1447	6.2343	0.29	32.02
NO_3	2.1166	1.6889	22.23	0.88
TN	2.0458	4.7909	24.64	35.01
TSS	3.9968	1.9487	16.79	11.56

Checking values of *Table 4*, it is found that: i) the standard deviation (sd) of the average NH_4 concentration in the WD is lower than in the NWD. This is an expected result due to the fact that in WD the nitrification is almost complete and NH_4 concentrations are very stable, below 1 mg/L. ii) the sd of the average NO_3 concentration in the WD is higher than in the NWD. This happens because NO_3 is generated during the nitrification process in the WD and fluctuates according to the variability of the system. This is not happening in NWD where NO_3 is around zero. iii) For the TN, the sd is lower in the WD than in the NWD. This happens because TN is the sum of nitrogenous compounds of different nature (inorganic compounds as well as nitrogen content of biomass) which are much more stable in WDs. iv) Finally, for the TSS the standard deviation is higher in the WD than in the NWD. The TSS is higher in the WD mostly because of the biomass generated during the nitrification-denitrification process what seems to provoke more variability in the mean value of TSS.

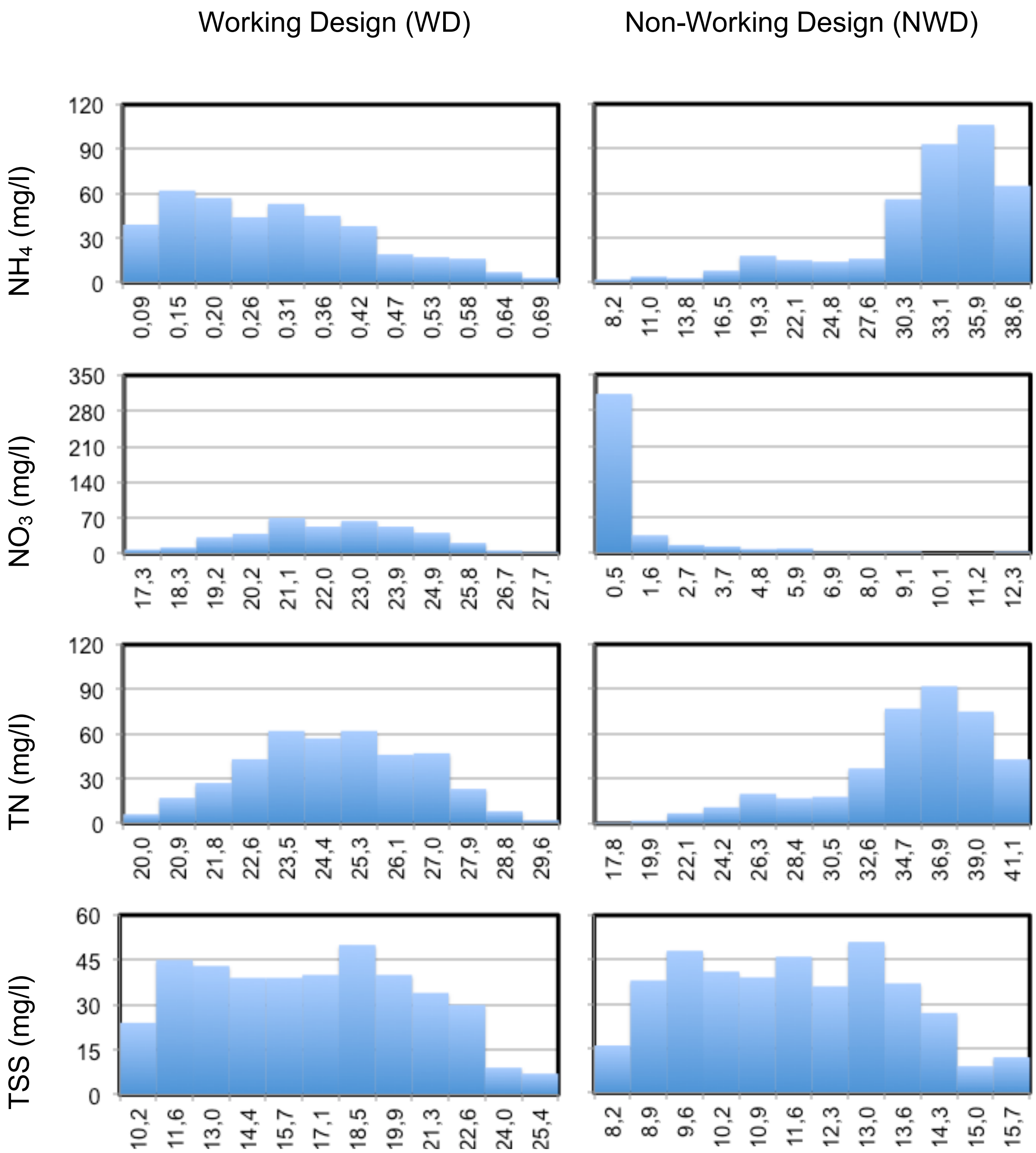

Figure 17. Histograms of average values of NH_4, NO_3, TN and TSS in the effluent for a Working Design (WD) and a Non-Working Design (NWD)

With respect to the normality of the distributions of the effluent concentrations for the working design, the Lilliefors test rejects the null hypothesis (that the distributions are normal) at a 5% significance level in the case of the NH_4 and TSS concentrations but not for the NO_3 and TN histograms. On the other hand and with respect to the normality of the distributions for the NWD results, the Lilliefors test rejects the null hypothesis (that the distributions are normal) at a 5% significance level in all cases.

The activated sludge processes occurring in WWTPs are highly non-linear and that is why most of the distributions are non-Gaussian. The distribution of the TN concentration of the WD seems to be normal probably because this variable aggregates the nitrogen content of the biomass as well as the ammonium and nitrate concentration. We found no explanation for the normality of nitrate in the WD. In this situation, the effort of performing the uncertainty analysis (400 simulations per design) is worthy since one could not approximate it analytically from the uncertainty ranges.

3.3 Evaluation of designs under uncertainty

This section explains how the 100 designs tested with respect to the Effluent Requirements and in terms of the Probability Of Compliance (POC), see *Table 3*. *Figure 18* shows the 5%, 50% and 95% percentiles obtained from the 100 designs together with the effluent requirements from *Table 1* (on the left the maximum and on the right the average values). First, it is observed that most of the designs are located in the flat (middle) part of the graph and just a few of them are on the extremes, which corresponds to WD or NWD designs. It is important to note that the design scenarios are sorted in descending order of their 50% percentile, for each one of the different effluent parameters considered. In consequence, a certain design appears with different abscissa value at each graph. For example, a design with a high ammonium removal performance will be positioned in the right part of the graph for the ammonium effluent values (both maximum and average), while it will have a medium position in the total nitrogen graphs and a quite left position for the total suspended solids (good performance of the denitrification and nitrification processes lead to relatively high values of solids in the effluent). The design scenarios with the 95% percentile lying below the reference value (see Table 1) would be working designs. Amongst the full range of design variables tested and the uncertainty propagated a minimal amount of designs are expected to satisfy the criteria imposed by the engineer. By also accepting design scenarios with the 50% percentile below the reference value there would be a risk of non-compliance when the WWTP would be build.

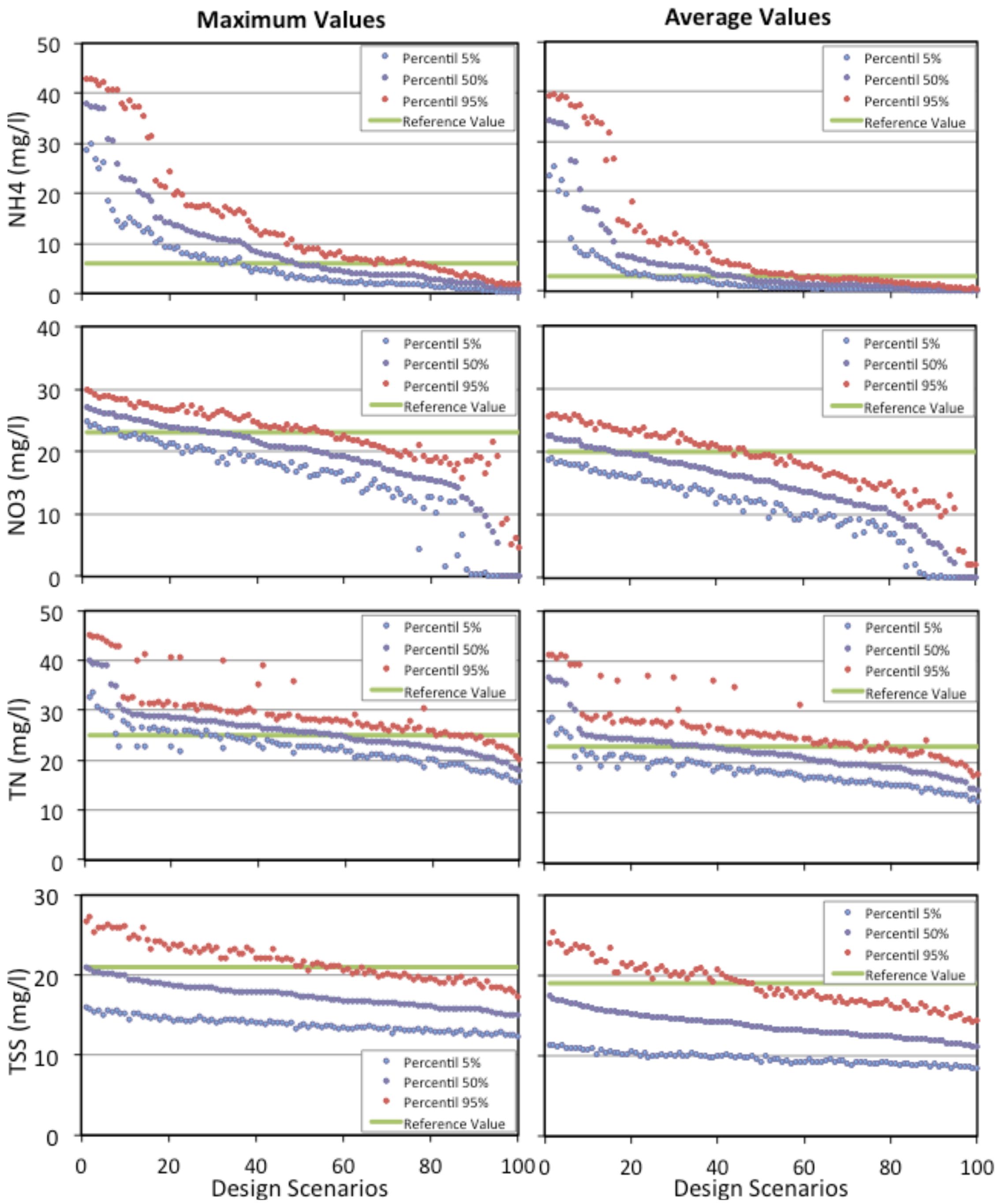

Figure 18.Median and 90% percentiles of the maximum and average values of the NH_4, NO_3, TN and TSS effluent concentrations.

Find in these results (*Figure 18)* shown for NH4+, NO3- and TN that the variability in the effluent concentrations is larger when comparing different design scenarios rather than when applying uncertainty ranges for a given design (*Figure 19*). On the contrary, in the case of TSS the associated uncertainty for a given design causes higher variation than the changes amongst design scenarios (*Figure 19*). This can be explained by the uncertainty associated with the settling parameters (*Table 3*). These sources of uncertainty might be inducing a higher impact in the

TSS effluent than considering a variety of designs even when including some plants that nitrify and others that do not.

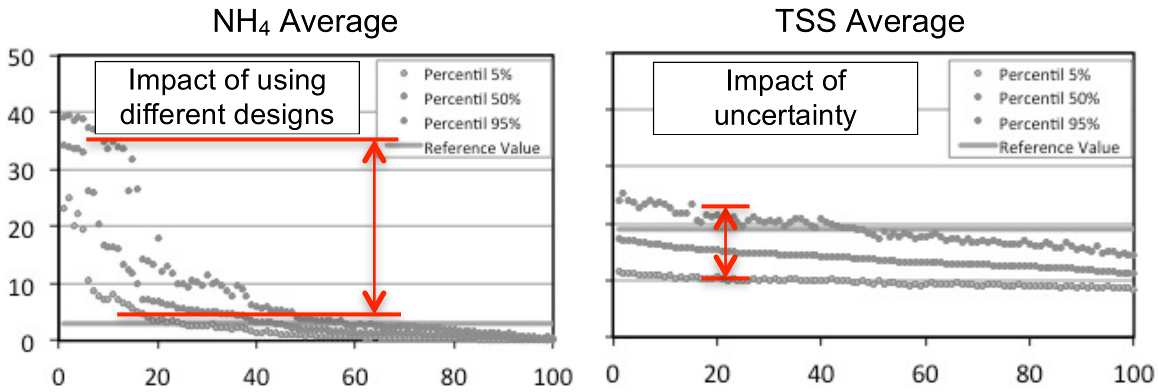

Figure 19. Comparison between NH_4 and TSS effluent values where it is seen that for NH4 the effect of varying the scenario is higher, whereas for TSS, uncertainty causes a higher impact.

Given the proximity of the maximum and average percentiles, in the following sections the results will be discussed in terms of their averages results.

3.4 Relationship between the different output variables

One of the most important issues of this project is to understand the relationship between the different parameters and design variables. A good starting point is to understand the relationships between the output variables, NH_4, NO_3, TN and TSS. It is important to remember that from now on, only average results will be used for the different assessments.

This section represents the relationship between NH_4, NO_3, TN and TSS, by analysing the distributions of the 100 average values of NH_4, NO_3, TN and TSS at their 85% percentile (*blue spots in Figure 20*) and their 95% percentile (*red crosses in Figure 20*). The relationship between these variables is also analysed by their correlation coefficients (*Table 5*). Analysing these relationships help to understand the system performance and to evaluate the design results:

Table 5.Relationship between the different output variables by the correlation coefficients.

r^2	NH_4	NO_3	TN	TSS
NH_4	-			
NO_3	0.70	-		
TN	0.69	0.20	-	
TSS	0.24	0.09	0.20	-

As seen in *Table 5* (and also in *Figure 20*), there is a quite strong correlation between NH_4 and NO_3 (r^2*=0.70*), note that for high values of NO_3, NH_4 is close to zero (WD) and when NO_3 is approximately zero (NWD) the NH_4takes very high values. This correlation is expected from the biological transformations by the nitrification and the denitrificacion processes (*see equation 1 and equation 2*). In the same way, there is also a quite strong relationship between NH_4 and TN (r^2*=0.69*) also shown in *Figure 20.* It can be seen that while this relationship is very strong for high values of NH_4 and TN, it becomes fuzzier for low values of ammonium and total nitrogen (in the WDs the TN is also affected by the biomass in the system while in the NWDs it coincides with the NH_4). The other relationships seem to be quite weak. Firstly, NH_4 and TSS show a correlation of r^2*=0.24,* although the main points of the graph are printed in the middle-left part, so it can be seen that in general low ammonium concentrations are related to high concentrations of Total Suspended Solids. The NO_3 and TN present a weak correlation as well (r^2*=0.20).* The same holds for the correlation between the Total Nitrogen and the Total Suspended Solids, which is quite weak (r^2*=0.20*), and it seems clear there is no correlation. Finally, the effluent concentrations of nitrates and total suspended solids have no correlation (r^2*=0.09*).

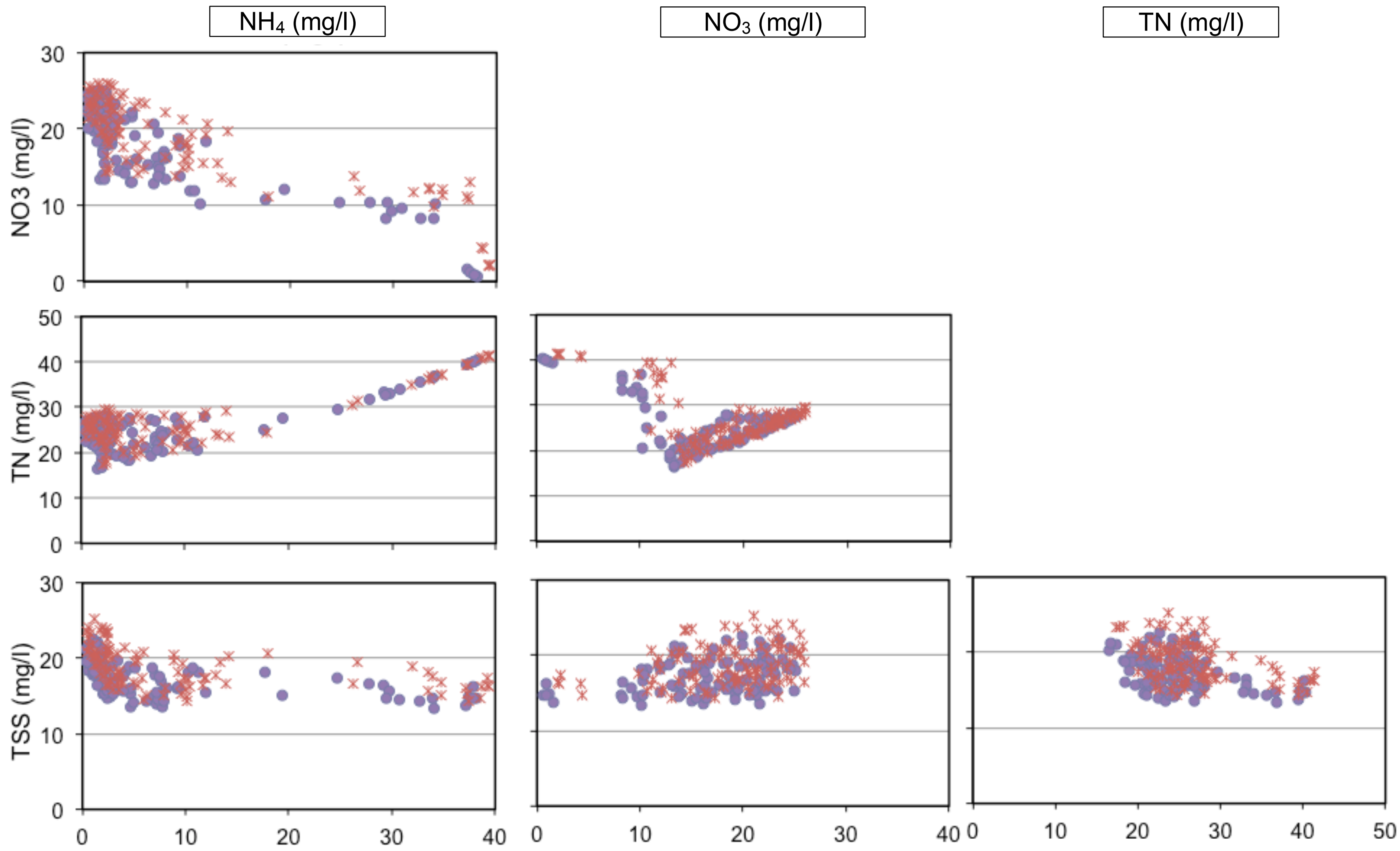

Figure 20. Relationships between the output variables expressed as 95% and 85% percentiles of the average values of NH_4, NO_3, TN and TSS in the effluent.

3.5 Discussion about Design Selection

One of the main goals of the project is to check the designs that fulfil the effluent requirements (Table 1) and try to understand their main characteristics. In this section, the designs that accomplish these limits will be analysed and commented. Thus, at the end of this section an idea about how to reach new and better designs will be proposed.

The different limits for effluent requirements were proposed in *Table 1* (*section 2.1.2.*) and graphically we can distinguish the designs that fulfil the effluent criteria by those that have results below all "Effluent Requirements" (green line in *Figure 18)*. As commented before the designs in *Figure 18* appear with different abscissa value for the different criteria. It is found that on the one hand, only 1 out of the 100 evaluated designs meets all the effluent requirements at 0.95 POC while on the other hand, 11 out of the 100 evaluated designs fulfil all effluent requirements with a POC of 0.85. This means that with 85% confidence the design accomplishes with the predefined effluent criteria.

Figure 21 represents the Waste Flow Rate against the Total Volume of the designs that fulfil the effluent requirements, with the 0.85 POC as blue spots, 0.95 POC with a red triangle and the Benchmark Simulation Model nº1 (default value) used to start the calculations with a green rhombus.

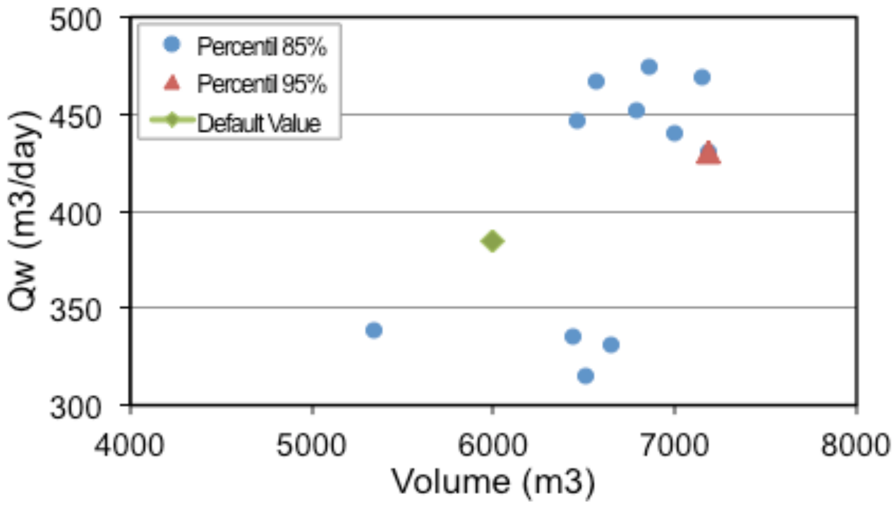

Figure 21. Relationship of the Volumes and Waste flow rates of the designs that fulfill the effluent requirements with 85% and 95% probability of compliance (POC).

Table 6 shows the numerical results represented in *Figure 21*, comparing the default design of BSM1 with the others obtained after applying the methodology of this work. Just one design (the #46) fulfils all the effluent requirements with a 0.95 POC or higher. Also, 10 designs accomplish with a 0.85 POC or higher. Table 6 also includes the percentage of volume or waste flow of each design with respect to the BSM1 (default design).

Table 6. Volumes and Waste flow rates of the designs that fulfil the effluent requirements with the percentages of excess or deficiency compared to the BSM1 design values.

POC	Designs	*Total Volume (m^3)*	%	Q_{waste} (m^3/day)	%
-	*BSM1*	6000	100	385	100
0.95	*Design 46*	7183.50	119.72	430.56	111.83
	Design 16	5337.00	88.95	338.33	87.88
	Design 24	6783.01	113.05	451.73	117.33
	Design 29	6852.99	114.22	474.85	123.34
	Design 50	6459.02	107.65	447.06	116.12
	Design 51	7154.54	119.24	469.27	121.89
0.85	*Design 72*	6504.49	108.41	315.46	81.94
	Design 75	6432.48	107.21	334.93	87.00
	Design 84	6993.51	116.56	439.79	114.23
	Design 85	6653.01	110.88	331.15	86.01
	Design 97	6567.03	109.45	467.09	121.32

To compare the different design proposals (designs in *Table 6*) it is important to note that the default design (BSM1) would fulfil the effluent requirements (*Table 1*) with nearly 0.85 POC. Therefore, and with respect to the uncertainty sources, each of the other designs represents an upgrade solution. Comparing the accepted designs with the BSM1one can come out with a couple of statements. Comparing the design 46, which fulfils the requirements with a POC of 0.95 or higher, with the BSM1 design it seems that a better design could be reached by enlarging the volume and increasing the waste flow rate (*119.72% of the volume and a 111.83% of the waste flow*) compared to the BSM1.

In the case that a POC of 0.85 could be accepted (a higher risk of not complying with the effluent requirements is accepted), it is found that 11 designs out of 100 are eligible. In this case, is not so clear that the designs would need higher volumes and waste flow rates since three of the designs accomplish the requirements with larger volumes but lower waste flow rates (*Design 72, Design 75 and Design 85*) or even one of them has both lower volume and waste flow rate (*Design 16*).

Therefore, a first conclusion can already be drawn: For this case study and only considering the effluent limits predefined before, *selecting higher volumes and/or waste flow rates does not necessarily guarantee higher probability of compliance*. The volumes and waste flow rates of the complying designs are not correlated (*Figure 21*). On the contrary, it is known that, according to the generally assumed criterion, the upgrading of the designs are achieved by either increasing the volumes or decreasing the waste flow rates (working at higher concentrations of total suspended solids in activated sludge).

In *Table 7* some more specific information about the selected designs can be found. It seems to be clear that one cannot take a decision about which designs are optimal by only looking at the total volume and waste flow rate. However, suspended solids in the mixed liquor (MLSS) is another important parameter.

Table 7 shows that all designs are working in a range of 2.800-3.800 mg/l of MLSS. Some of the most optimised designs in terms of keeping low volumes and waste flow rates while guaranteeing a POC over 0.85 present high MLSS values (*Design 16, Design 72 and Design 75*). In the limit, the optimum one (*Design 16*) is the one with the highest MLSS values. The result should be carefully considered because high values of MLSS might promote the development of filamentous bacteria (*Metcalf & Eddy, 2003*) that cause problems such as (worse settling and lower diffusion of dissolved oxygen and nutrients). It is important to note that the mathematical model used for these simulations is not able to represent this phenomenon so engineers' knowledge is crucial in this point.

Table 7. Main characteristic values of the different design parameters for selected models.

Designs	Total Volume (m^3)	Aerobic fraction	Q_{Waste} (m^3/d)	$Q_{Int}/1.25$ (m^3/h)	Q_{Ext} (m^3/h)	MLSS (mg/L)
BSM1	6000	0.22	385	55338.00	18446.00	
Design 16	5337.00	0.62	338.33	43069.40	12818.18	3788.87
Design 24	6783.01	0.61	451.73	31819.50	18275.23	3357.12
Design 29	6852.99	0.60	474.85	40176.51	13673.66	2867.91
Design 46	7183.50	0.61	430.56	36197.31	11618.84	2872.91
Design 50	6459.02	0.63	447.06	36222.49	15164.72	3170.15
Design 51	7154.54	0.63	469.27	35424.69	14738.98	2975.78
Design 72	6504.49	0.56	315.46	52051.76	11713.65	3761.32
Design 75	6432.48	0.64	334.93	38487.66	12256.46	3659.01
Design 84	6993.51	0.65	439.79	32069.16	13276.48	3008.80
Design 85	6653.01	0.55	331.15	37496.43	11621.94	3589.40
Design 97	6567.03	0.59	467.09	51050.50	15575.83	3083.63

Figure 23 shows the different designs that achieve the requirements in terms of the two hypothetic fronts. Pareto Front is the tool that will help the problem-solver to choose the optimum design.

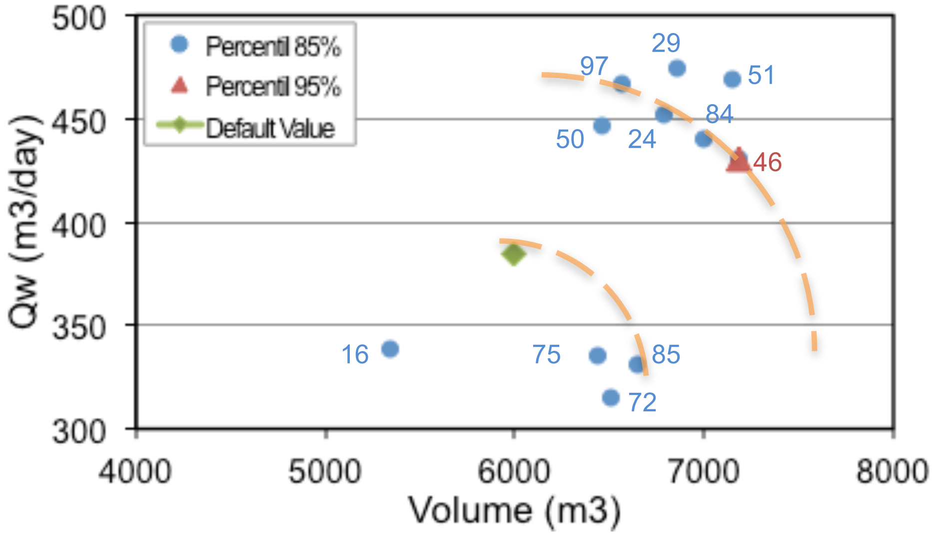

Figure 23. Different designs that fulfil the effluent requirements with 95% and 85% probability of compliance (POC) and two Front drawn.

As seen in *Figure 23* there are 3 clearly defined clouds of spots (designs) spread around the graph. Drawing a front of solutions the optimum model would be the design number 16. It seems clear that taking less volume and lower waste flow rate, which means less costs, an optimum design can be built. In case that the cost of the waste sludge is very high one could prefer solutions with larger volumes (design 72, design 75 or design 85).

In the case that the utility decides to work on MLSS values lower than 3.500 mg/l, one would need to move to the second front (*Design, 24, Design 29, Design 46, Design 50, Design 51, Design 84 and Design 97*). According to, *Typical design parameters for commonly used activated sludge processes (*Metcalf & Eddy, 2003*)* the optimum range of MLSS for conventional plug flow plants should be between 1000 mg/L and 3000 mg/L. So, according to these requirements, only 3 designs remain possible: design 29, design 46 and design 51. The decision now is clear since *Design 46* guarantees a POC higher than 0.95 at the only expense of needing a slightly larger volume.

These results prove that the optimum design corresponds rather with a good combination of design values and that it cannot be explained by single relationships generally assumed on the design variables (volume, flow, solids, etc.). Nevertheless, the results of this analysis should not be taken as a paradigm for WWTP design but only as an example of the potential of the new tool for

WWTP design under uncertainty. Obviously, the prototype tool should be tailored for the specific characteristics of each case study (main uncertainties; boundaries of volume; availability of new technologies; effluent requirements, etc.).

4 BUDGET SUMMARY

The total budget for the final project, which is broken down in the following **Table 8**,amounting to a total of **5.946,00 €.**

Table 8.Budget Summary.

Equipment	***Unit Price (€/h)***	***Time spent (h)***	***Total Price (€)***
Computer depreciation	0,04	650	26,00
Software license depreciation	0,05	2.900	145,00
Printing / Photocopying			15,00
		TOTAL COST EQUIPMENT	**186,00**
Labour	***Unit Price (€/h)***	***Time spent (h)***	***Total Price (€)***
Researcher staff			
Meetings: Supervision of the work	90,00	30	2.700,00
Review of results and writing	90,00	10	900,00
Student			
Process of information gathering	0,00	300	0,00
Development of the tool	12,00	100	1.200,00
Analysis and comparison of the selected case study	0,00	30	0,00
Writing of the project	8,00	120	960,00
		TOTAL COST OF LABOR	**5.760,00**
		TOTAL COST	**5.946,00**

5 CONCLUSIONS

The potential of a new tool for design of WWTPs under uncertainty has been shown. The design of a benchmarked wastewater treatment plant has been analysed taking into account the most important sources of uncertainty. The main conclusions are:

- A dynamic simulation model that describes the dynamics of the process and features the daily and weekly patterns of the influent wastewater has been successfully used. The simulation model can be used for design accounting for the dynamics of the system.
- The sources of uncertainty have been taken into account by performing an Uncertainty Analysis. The uncertain factors have led to considerable differences in the water quality parameters in the effluent. Accounting for uncertainty is important to see whether the variability of the effluent concentrations is more influenced by the different design scenarios or by the sources of uncertainty.
- A new prototype design tool has been presented which can provide not only optimum design solutions but also reports their probability of compliance with respect to some effluent requirements. For this particular case study, it has been found that while the default design could fulfil the effluent requirements, another solution should be proposed if it is necessary to guarantee a probability of compliance of 0.85 or higher.

It has been proved that knowledge have to be applied when checking the final results because the apparently optimum solutions might lead to important operation problems. For example, working at high levels of Mixed Liquor Suspended Solids can provoke flocculation problems that the current simulation model does not predict.

The main advantage of using this methodology in comparison with the traditional design guidelines is that it allows estimating the probability of compliance of a certain design. In consequence, the engineering firm or consultancy will be better informed about the risks assumed and will therefore be able to adopt more robust design solutions. Further research should be carried out to come up with a general design methodology under uncertainty. For example, it would be very interesting to include a proper analysis of the cost of building different designs.

Girona, 3rd of September of 2012

Josep Altimir i Puigdemont.

6 REFERENCES

ATV-DVWK, 2000. *A 131E Dimensioning of Single-Stage Activated Sludge Plants*. German Association for Water, Wastewater and Waste, Hennef, Germany.

Benedetti, L., D. Bixio and P.A. Vanrolleghem, 2006. Benchmarking of WWTP design by assessing costs, effluent quality and process variability. Water Science & Technology, 54 (10), 95–102.

Bixio, D., G. Parmentier, D. Rousseau, F. Verdonck, J. Meirlaen, P.A. Vanrolleghem and C. Thoeye, 2002.A quantitative risk analysis tool for design/simulation of wastewater treatment plants, *Water Science & Technology*, 46 (4-5), 301-307.

Copp, J.B., 2001 *The COST Simulation Benchmark – Description and Simulator Manual.*Office for Official Publications of the European Community, Luxemburg.

Corominas, L., X. Flores-Alsina, D. Muschalla, M.B. Neumann and P.A. Vanrolleghem, 2010.Verification of WWTP design guidelines with activated sludge process models, paper presented at WEFTEC 2010, New Orleans, USA, October 2-6.

Dold, P.L., G.A. Ekama and G.v.R. Marais, 1980.A general model for the activated sludge process, Prog.Water.Technol. 12, pp. 47–77.

Ten State Standardsfor Wastewater Facilities, 2004. *Policies for the Design, Review, and Approval of Plans and Specifications for Wastewater Collection and Treatment Facilities.*

Flores-Alsina X., I. Rodriguez-Roda, G. Sin and K.V.Gernaey, 2008.Multi-criteria evaluation of wastewater treatment plant control strategies under uncertainty. Water Res. 42(17), 4485-4497.

Henze, M., W. Gujer, T. Mino and M. van Loosdrecht, 2000. Activated Sludge Models ASM1, ASM2, ASM2d and ASM3. *Scientific and Technical Report No. 9*, IWA Publishing, London.

McIntyre, N., B. Jackson, H. S.Wheater and S.Chapra,2002. Role of numerical efficiency in the viability of Monte Carlo simulation of the environment—a case study of river thermodynamics. J. Environ. Engng. (ASCE).

McKinney, R.E., and R.J.Ooten, 1969. “Concepts of complete mixing Activated Sludge”. Trans. 19th Eng. conf., Univ.Of Kansas, 32.

Metcalf & Eddy, G. Tchobanoglous, F. L. Burton and H. D. Stensel, 2003. *Wastewater Engineering, Treatment and Reuse*, Fourth Edn, McGraw Hill Education.

Papadopoulos, C. E. and H. Yeung, 2001. "Uncertainty estimation and Monte Carlo simulation method". Flow Measurement and Instrumentation, 12(4): 291-298.

Ráduly, B., K.V. Gernaey, A.G. Capodaglio, P.S. Mikkelsen and M. Henze, 2007.Artificial neural networks for rapid WWTP performance evaluation: Methodology and case study. Environmental Modelling& Software, 22, 1208-1216.

Ramin, E., G. Sin, P.S. Mikkelsen and B.G. Plósz, Significance of uncertainties derived from settling tank model structure and parameters on predicting WWTP performance: A global sensitivity analysis study, paper presented at the 8th IWA Symposium on Systems Analysis and Integrated Assessment (Watermatex2011), San Sebastián, Spain, June 20-22, 2011.

Rivas, A., I. Irizar and E. Ayesa, 2008. Model-based optimisation of Wastewater Treatment Plants design. Environmental Modelling& Software, 23, 435-450.

Rousseau, D., Verdonck, F., Moerman, O., Carrette, R., Thoeye, C., Meirlaen, J. and Vanrolleghem, P.A., 2001. Development of a risk assessment based technique for design/retrofitting of WWTPs. Water Science and Technology, 43(7), 287 – 294

Sin, G., K.V. Gernaey, M.B. Neumann, M.C.M. van Loosdrecht and W. Gujer, 2011. Global sensitivity analysis in wastewater treatment plant model applications: Prioritizing sources of uncertainty. Water Research, 45, 639-651.

Sin, G., K.V. Gernaey, M.B. Neumann, M.C.M.Van Loosdrecht, W.Gujer, 2009.Uncertainty analysis in WWTP model applications: a critical discussion using an example from design. Water Research, 43, 2894-2906.

Takács, I., G. Patry and D. Nolasco, 1991.A dynamic model of the clarification-thickening process, Water Research, 25, 1263-1271.

Willems, P., and J. Berlamont, 2002. "Probabilistic emission and immission modelling: case-study of the combined sewer - WWTP - receiving water system at Dessel (Belgium)." Water Science and Technology, 45(3), 117-124.

Girona, 3rd of September of 2012

Josep Altimir i Puigdemont.

7 GLOSSARY

ASM1	Activated Sludge Model No 1
BOD	Biological Oxygen Demand [mg/L]
BSM1	Benchmark Simulation Model No 1
COD	Chemical Oxygen Demand [g COD m^{-3}]
DO	Dissolved Oxygen [g $O_2 m^{-3}$]
IWA	International Water Association
LHS	Latin Hypercube Sampling
MC	Monte Carlo
MLSS	Mixed Liquor Suspended Solids [g TSS m^{-3}]
N	Nitrogen
Q	Influent flow rate [$m^3 day^{-1}$]
Q_{INT}	Internal recycle flow rate [$m^3 day^{-1}$]
S_{NH4}	Effluent ammonium concentration [g N m^{-3}]
S_{NO3}	Effluent nitrate concentration [g N m^{-3}]
SRT	Sludge retention time [days]
TSS	Total suspended solids [g TSS m-3]
V_{AER}	Aerobic Volume [m^{-3}]
V_{ANOX}	Anoxic Volume [m^{-3}]
WWTP	Wastewater Treatment Plant