SEBTEMBER 2020 Ph.D. in Electrical and Electronics Engineering BAYRAM ARDA KUŞ

REPUBLIC OF TURKEY

GAZİANTEP UNIVERSITY

GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES

DEVELOPMENT AND TESTING OF A GRAPHICAL SIMULATOR FOR WASTEWATER TREATMENT PLANT DESIGN AND ANALYSIS

Ph.D. THESIS

IN

ELECTRICAL AND ELECTRONICS ENGINEERING

BY

BAYRAM ARDA KUŞ

SEPTEMBER 2020

DEVELOPMENT AND TESTING OF A GRAPHICAL SIMULATOR FOR WASTEWATER TREATMENT PLANT DESIGN AND ANALYSIS

Ph.D. Thesis

in

Electrical and Electronics Engineering

Gaziantep University

Supervisor

Assoc. Prof. Dr. Tolgay KARA

by

Bayram Arda KUŞ

September 2020

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Bayram Arda KUŞ

ABSTRACT

DEVELOPMENT AND TESTING OF A GRAPHICAL SIMULATOR FOR WASTEWATER TREATMENT PLANT DESIGN AND ANALYSIS

KUŞ, Bayram Arda
Ph.D. in Electrical and Electronics Engineering
Supervisor: Assoc. Prof. Dr. Tolgay KARA
September 2020
90 pages

In this study, a computer based graphical interface is developed to improve wastewater treatment systems. Depending on the desired input-output relationship of the system, the simulator is run to show the possible results for each step of the processes of a wastewater treatment system. In order to describe the treatment performance on the wastewater, each subsystem responses, which are predefined and mathematically modeled, are observable. It is possible to observe the system behavior on maximum and minimum values of physical, biological and chemical wastewater components. The subsystems are constructed elastically; the simulator allows adding different mathematical responses to the subsystems on different chemical and physical components. The organic-inorganic and chemical-physical responses of the system are simulated distinctly. The wastewater treatment characteristics for different components of any type are planned, observed and optimized. All relevant variables such as depth of pools, flow speed and sewage characteristics can be changed on the simulator. Whale Optimization Algorithm (WOA) is used to achieve the desired optimized solutions. The simulator is run for the Gaziantep Oğuzeli WWTP conditions. The results of whole simulator are concluded with both economic and environmental trajectories depending on the desired outputs and the control mechanisms of the system. Moreover a Unified Tank Model (UTM) for the aeration and sedimentation phases is proposed and investigated as part of this study. Environmental aspects are taken in to account for all steps of this study.

Key Words: Wastewater, Wastewater Treatment, Mathematical Modeling, Simulation, Control.

ÖZET

ATIKSU ARITMA TESİSİ TASARIMI VE ANALİZİ İÇİN GRAFİKSEL SİMÜLATÖR GELİŞTİRİLMESİ VE TEST EDİLMESİ

KUŞ, Bayram Arda
Doktora Tezi, Elektrik Elektronik Mühendisliği
Danışman: Doç. Dr. Tolgay KARA
Eylül 2020
90 sayfa

Bu çalışmada atıksu arıtma sistemlerinin iyileştirilmesi için bilgisayar tabanlı bir grafik arayüz geliştirilmiştir. Sistemin istenen girdi-çıktı ilişkisine bağlı olarak, simülatör, bir atık su arıtma sisteminin işlemlerinin her bir aşaması için olası sonuçları göstermek üzere çalıştırılır. Atık su arıtma performansını tanımlamak için, önceden tanımlanmış ve matematiksel olarak modellenen her bir alt sistemin davranışı gözlemlenebilir. Sistem davranışını, fiziksel, biyolojik ve kimyasal atık su bileşenlerinin maksimum ve minimum değerlerinde gözlemlemek mümkündür. Alt sistemler elastik olarak inşa edilmiştir; simülatör, farklı kimyasal ve fiziksel bileşenler üzerindeki alt sistemlere farklı matematiksel yanıtlar eklemeyi sağlar. Sistemin organik-inorganik ve kimyasal-fiziksel tepkileri belirgin bir şekilde simüle edilmiştir. Herhangi bir tipteki farklı bileşenler için atıksu arıtma özellikleri planlanmış ve optimize edilmiştir. Simülatör üzerinde değişiklik yapmak için havuz derinliği, akış hızı ve atıksu özellikleri. ile ilgili tüm değişkenler mevcuttur. Optimize edilmiş çözümlere ulaşmak için Balina Optimizasyon Algoritması (WOA) kullanılmıştır. Simülatör, Gaziantep, Oğuzeli AAT koşulları ile yürütülmüştür. Bütün bir simülatörün sonuçları istenen çıktılara ve sistemin kontrol mekanizmalarına bağlı olarak hem ekonomik hem de çevresel yörüngelerle sonuçlandırılmıştır. Ayrıca, bu çalışmanın bir parçası olarak havalandırma ve sedimantasyon aşamaları için Birleşik Tank Modeli (UTM) önerilmiş ve araştırılmıştır. Bu çalışmanın tüm aşamalarında çevresel kaygılar dikkate alınmıştır.

Anahtar Kelimeler: Atıksu, Atıksu Arıtımı, Matematiksel Modelleme, Simulasyon, Kontrol.

Hayatlarını benimle paylaşan yol arkadaşlarım;

Emine, Müslüm, Dilan, Ardıl ve Ada ya.…

My companions who share their lives with me;

To Emine, Müslüm, Dilan, Ardıl and Ada.

ACKNOWLEDEMENTS

I would not be so hopeful if I did not know that change is an obligation for humanity, and even nature itself. I firmly believe that every defeat is a new beginning with experience from defeat. This belief in change has allowed me to live far away from my family for the last five years.

I would like to thank my dear parents; **Müslüm and Emine KUŞ** for their lovingly and sincere support in all matters.

Special thank for **Assoc. Prof. Dr. Tolgay KARA,** it is impossible for me to forget his precious endeavor. I am grateful for his polite attitude, although I have disturbed him so much timelessly. I would also like to thank **Prof. Dr. Ergun ERÇELEBİ, Assoc. Prof. Dr. Alkan ALKAYA, Prof. Dr. Arif NACAROĞLU, Prof. Dr. Kaan YETİLMEZSOY** and **Dr. Mehmet ARICI** for their valuable comments, experiences and contributions.

Thank you to **Dr. Eda ADAL** for having patiently encouraged me more than once. She is definitely a great friend! Thank you to **Dr. Muhammed Umair KHAN** for sharing his valuable experiences with me.

My colleagues **Tayfun YILMAZ, Yusuf AK** and **Hamdi BEŞLİ** I am honored to be their friend, and I am thankful for their support and patience. I also thank **Ömer YAZAR** for his devoted support.

And my pieces that complement me; **Dilan**, **Ardıl** and **Ada**. I have mentioned about the change and my belief in it. I have full faith in you and the change. Maybe you will change…

TABLE OF CONTENTS

Page

ABSTRACT .... **v**

ÖZET .... **vi**

ACKNOWLEDGEMENTS .... **viii**

TABLE OF CONTENTS .... **ix**

LIST OF TABLES .... **xi**

LIST OF FIGURES .... **xii**

LIST OF SYMBOLS .... **xiv**

LIST OF ABBREVIATIONS .... **xviii**

CHAPTER I **1**

INTRODUCTION **1**

1.1. General 1

1.2. Motivation of Study 2

1.3. Objectives of Study 3

1.4. Organization of Thesis 5

CHAPTER II **7**

LITERATURE REVIEW **7**

2.1. Historical Development of WWT and WWTP 7

2.2. Development of WWTP Control and Simulations 9

2.3. Brief Information of Process 14

2.3.1. Physical Treatment 15

2.3.2. Chemical Treatment 16

2.3.3. Biological Treatment 17

2.4.4. Advanced WWT 20

2.4.5. Disinfection and Release 21

CHAPTER III **22**

OPTIMIZATION **22**

3.1. Whale Optimization Algorithm 24

CHAPTER IV **27**

MATHEMATICAL MODELING **27**
4.1. Biomass and Substrate Equilibrium 28
4.2. Modeling of a Single Substrate System 31
4.3. Activated Sludge Model 32
4.3.1. Carbonaceous Components 35
4.3.2. Nitrogenous Components 36
4.4. Sedimentation Tank and Aeration System Models 40
4.4.1. Sedimentation Tank Model 40
4.4.2. Aeration System 43
4.7. UTM Concept 45
4.7.1. Mathematical Model of Unified Tank Volume 48
CHAPTER V **52**
SIMULATOR DESIGN **52**
5.1. Methodology 52
5.2. Computer Application 53
CHAPTER VI **61**
CASE STUDY: GAZİANTEP OĞUZELİ WWTP **61**
6.1. Plant Characteristics 61
6.2. Simulation Test Results 63
6.2.1. Simulation Tests on Existing Plant 63
6.2.2. Simulation Tests on Proposed UTM Design 66
6.3. Summary and Discussions 69
CHAPTER VII **71**
CONCLUSION **71**
7.1. Recommendations for Future Work 72
REFERENCES 73
PUBLICATIONS 88
CIRRICULUM VITAE 89

LIST OF TABLES

Page

Table 4.1 Two-State / One Process model in Petersen matrix format....................... 31

Table 4.2 Process-variables and parameters in ASM1 33

Table 6.1 Influent-effluent water characteristics of Oğuzeli WWTP........................ 64

Table 6.2 RMSE values for conventional and optimal UTM designs....................... 69

Table 6.3 RMSE values for simulator and optimal operation conditions in a summer day.. 70

Table 6.4 RMSE values for simulator and optimal operation conditions in a winter day 70

LIST OF FIGURES

Page

Figure 1.1 A butterfly in reality and a model 2
Figure 2.1 A general view of WWTP 8
Figure 2.2 A general view of SBR type WWTP 9
Figure 2.3 A schematic presentation of a system on GPS-X 10
Figure 2.4 A schematic presentation of a system on BioWin 11
Figure 2.5 A graphical presentation of a system on BioWin 12
Figure 2.6 A schematic presentation of a system on WEST 13
Figure 2.7 Graphical presentations of ammonia, nitrate and total P changes during the process 13
Figure 2.8 Schematic presentation of the WWT plant 15
Figure 2.9 Electro mechanic screening system of WWT plant 15
Figure 2.10 A general view of oxidation ditch 18
Figure 2.11 Fuchs type aeration 18
Figure 2.12 Secondary sedimentation tank 19
Figure.2.13 Schematic diagram of activated sludge treatment process 19
Figure 3.1 Typical-optimized operation comparison 22
Figure 3.2 Whales' bubble-net feeding behavior 25
Figure 4.1 Grey box modeling 27
Figure 4.2 Modeling strategy algorithm 28
Figure 4.3 WWT flow diagram 28
Figure 4.4 Schematic diagram of activated sludge treatment process 29
Figure 4.5 ASM1 model structure 35
Figure 4.6 Carbonaceous components 36
Figure 4.7 Nitrogenous components 37
Figure 4.8 Optimal location of diffusers 41
Figure 4.9 WOA objective space 41
Figure 4.10 Layer discretization 42
Figure 4.11 Electrical analogy of the aeration system model simulation setup 45

Figure 4.12 Sequencing batch reactor operation system adapted to UTM 46
Figure 4.13 Unified tank model 47
Figure 4.14 UTM aeration system 51
Figure 5.1 Main system algorithm 53
Figure 5.2 General Schematization of the WWTP graphical simulator.................... 55
Figure 5.3 Schematization of the WWTP model of screening block........................ 56
Figure 5.4 Schematization of the WWTP model charging and discharging block ... 57
Figure 5.5 Schematization of the WWTP model pump block 57
Figure 5.6 Schematization of the WWTP model oxidation block 58
Figure 5.7 Schematization of the WWTP model for aeration system block............. 58
Figure 5.8 Schematization of the WWTP model retention time block 59
Figure 5.9 Schematization of the WWTP model total efficiency block 60
Figure 6.1 Annual influent-effluent characteristics of Oğuzeli WWTP 62
Figure 6.2 Dissolved oxygen characteristics on a winter day 63
Figure 6.3 Grid simulations for on a winter day (December 1st, left), and a summer day (July 1st, right) 65
Figure 6.4 Annual existing (left) and optimized (right) grid simulations 65
Figure 6.5 Winter day (December 1st) optimized grid simulations.......................... 65
Figure 6.6 DO simulations on a winter day (December 1st, left), and a summer day (July 1st, right)... 66
Figure 6.7 DO optimized simulations on a winter day (December 1st, left), and a summer day (July 1st, right) 66
Figure 6.8 Dissolved oxygen simulation in UTM on a winter day........................... 67
Figure 6.9 Optimized aeration system behavior in UTM on a winter day................ 68

LIST OF SYMBOLS

$\vec{\mathbf{A}}$	coefficient vector
$\mathbf{A_0}$	cross-sectional area of the orifice (m^2)
$\mathbf{A}$	the parameters in the solid stress function σ_e.
$\vec{\boldsymbol{\alpha}}$	linearly decreased vector from 2 to 0 driven by iterations
$\boldsymbol{\alpha_1}$	parameter in the dispersion
$\boldsymbol{\alpha_2}$	parameter in the dispersion
$\mathbf{b}$	a positive constant
$\boldsymbol{\beta}$	the parameter in the solid stress function σ_e.
$\mathbf{b_A}$	autotrophic decay rate, d^{-1}
$\mathbf{b_H}$	heterotrophic decay rate, d^{-1}
$\vec{\mathbf{C}}$	coefficient vector
$\mathbf{C_c}$	concentration constant
$\mathbf{C_d}$	discharge coefficient
$\mathbf{C_V}$	velocity constant
$\mathbf{c_j}$	concentration on j^{th} layer
$\vec{\mathbf{D}}$	distance between whale position and prey position
Dr	effective diffuser radius
$\mathbf{d}$	water density
$\mathbf{d_{comp}(C)}$	compression term
$\mathbf{d_{disp}}$	dispersion coefficient
$\mathbf{d_{disp}(z, Q_f(t))}$	dispersion term
$\mathbf{d_0}$	diameter of orifice
F	food
$\mathbf{F(C, z, t)}$	convective flux function which represents the hindered settling flux with bulk flows
$\mathbf{f_{bk}}$	bulk flux
$\mathbf{g}$	gravity constant (9.81 m/s^2)

H	air diffuser submerging depth
$\mathbf{h_f}$	the final height of the fluid (m)
$\mathbf{h_i}$	the initial height of the fluid (m)
Θ	temperature (in Celsius degrees)
J	performance function
j	layer within the sedimentation tank
$\mathbf{K_o}$	Monod's constant
$\mathbf{K_{NH}}$	ammonia half saturation coefficient for autotrophs, g COD m^{-3}
$\mathbf{K_{NO}}$	nitrate half saturation coefficient for denitrifying heterotrophs, g NO_3 -N m-
$\mathbf{K_{O,H}}$	half saturation coefficient for heterotrophs, g O_2 m^{-3}
$\mathbf{K_{OA}}$	oxygen half saturation coefficient for autotrophs, g O_2 m^{-3}
$\mathbf{K_s}$	half saturation coefficient for heterotrophs, g COD m^{-3}
$\mathbf{K_x}$	half saturation coefficient for hydrolysis of slowly biodeg. substrate, g slowly biodeg. COD $(\text{g cell COD day})^{-1}$
$\mathbf{k_A}$	ammonification rate, m^3/ (g COD day)
$\mathbf{k_{La}}$	oxygen transfer function
$\mathbf{k_{La}(Q_{air})}$	a function describes the oxygen transfer and depends on the aeration system and sludge conditions
$\mathbf{k_h}$	maximum specific hydrolysis rate, g slowly biodeg.,COD $(\text{g cell COD day})^{-1}$
L1, L2	pool dimensions
M	mass
$\hat{\mu}_A$	aerobic maximum specific growth rate, 1/d
$\hat{\mu}_H$	heterotrophic maximum specific growth rate, 1/d
Nd	number of diffusers
N	denotes the number of samples
$\mathbf{n_g}$	correction factor for anoxic growth of heterotrophs
η_h	correction factor for anoxic hydrolysis
$\mathbf{p_a}$	represents atmospheric pressure
$\mathbf{P_c}$	main pipe pressure
$\mathbf{P_h}$	hydrostatic pressure drop

$\mathbf{P_r}$	pressure drop across the blower
Pr	a random number that presents the bubble-net method of whales which prey randomly
Pn%	pressure tolerance of diffusers for efficient performance
$\mathbf{Q_{air}}$	airflow
$\mathbf{Q_c}$	main pipe airflow
$\mathbf{Q_g}$	airflow through the pipe
$\mathbf{QS_{in}}$	influent substrate
$\mathbf{QS_{out}}$	effluent substrate
R	respiration
$\mathbf{R_1}$	bottom radii of UTM
$\mathbf{R_2}$	top radii of UTM
$\mathbf{R_d}$	diffuser resistance
$\mathbf{R_g}$	pressure drop across the pipe
$\mathbf{R_r}$	fluid-flow resistance is represented
$\vec{\mathbf{r}}$	random vector
$\mathbf{r_{O_2}}$	proportion of oxygen in the air
r	sludge recirculation ratio (or the return sludge ratio)
$\boldsymbol{\rho_f}$	density of the fluid
$\boldsymbol{\rho_s}$	density of the flocculated solids
$\mathbf{S_i}$	soluble inert organics (g COD/m^3)
$\mathbf{S_S}$	readily biodegradable (soluble) substrate (g COD/m^3)
$\mathbf{S_{NO}}$	nitrate and nitrite (g N/m^3)
$\mathbf{S_{NH}}$	free and ionized ammonia (g N/m^3)
$\mathbf{S_{ND}}$	soluble biodegradable organic nitrogen (in Ss)(g N/m^3)
So	dissolved oxygen concentration (g O_2/m^3)
$\mathbf{S_O}^{\mathbf{ref}}$	reference dissolved oxygen concentration
$\mathbf{So_{sat}}$	dissolved oxygen saturation concentration
$\mathbf{SSV_{30}}$	settled sludge volume at 30 minutes of settling time
$\sum \mathbf{m^*_{in}}$	total input mass flow rate (kgf/s)
$\sum \mathbf{m^*_{out}}$	total output mass flow rate (kgf/s)

$\mathbf{T}$	calculated discharge time (s)
$\mathbf{T_{exp}}$	experimental discharge time (s)
$\mathbf{V}$	volume of reactor
$\mathbf{V_0}$	theoretical jet velocity m/s
$\mathbf{V_c}$	main pipe volume
Wa	wall steep angle
Wd	water depth
$\mathbf{X}$	biomass concentration
$\mathbf{X_{B,A}}$	active autotrophic biomass (g COD/m^3)
$\mathbf{X_{B,H}}$	active heterotrophic biomass (g COD/m^3)
$\mathbf{X_i}$	particulate inert organics (g COD/m^3)
$\mathbf{X_{ii}}$	inert inorganic suspended solids (g/m^3)
$\mathbf{X_{ND}}$	particulate biodegradable organic N (in Xs)(g N/m^3)
Xp	unbiodegradrable particulates from cell decay (g COD/m^3)
$\overrightarrow{\mathbf{X_p}}(\mathbf{t})$	prey position
$\mathbf{X_S}$	slowly biodegradable (particulate) substrate (g COD/m^3)
$\overrightarrow{\mathbf{X_w}}(\mathbf{t})$	whale position
$\mathbf{Y}$	growth yield
$\mathbf{Z}$	sludge blanket height

LIST OF ABBREVIATIONS

ASM	Activated Sludge Model
ARMAX	Autoregressive Moving Average eXogenous
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
CSRT	Continuously Stirred Reactor Tank
CV	Calculated Volume
DO	Dissolved Oxygen
GA	Genetic Algorithm
IAWPRC	International Association on Water Pollution Research and Control
IEA	International Energy Association
IWA	International Water Association
MBBR	Moving Bed Biofilm Reactor
MBR	Membrane Bioreactor
MLSS	Mixed Liquor Suspended Solids
PSO	Particle Swarm Optimization
RAS	Return Activated Sludge
RMSE	Root Mean Square Error
SBR	Sequential Batch Reactor
SCADA	Supervisory Control and Data Acquisition
SVI	Sludge Volume Index
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TSS	Total Suspended Solids
UTM	Unified Tank Model
VoSS	Volume of Settled Sludge
WOA	Whale Optimization Algorithm
WWT	Wastewater Treatment

WWTP	Wastewater Treatment Plant

CHAPTER I

INTRODUCTION

1.1 General

Life begins with water. Clean water is the most essential material for human beings to survive, although the source of clean water is very limited compared with the increase of population worldwide. To prevent ecological collapse, humanity has to ask the question at every step on their expenditures “How much is enough?". It does not mean "more" is always "better" [1].

Over-consumption behavior is not an indicator of development at both country and individual level. Furthermore, the unplanned and excessive investments cause deterioration on both ecology and economy [2]. On the one hand, the poorest populations in the world such as Afghanistan, Bangladesh, Brazil, Colombia, Equatorial Guinea, Gambia, Haiti, India, Palestine (Gaze Strip), Yemen and Syria are trying to survive. These countries suffer from inadequate water and sanitation investments and cannot access water for different reasons. On the other hand, the rest of the world drink more mineral water than tap water or they transport drinking water across the ocean [3].

Like drinking water, it is also important that wastewater is discharged into nature under certain conditions. Polluted environment and affected organisms can also affect human life dependent on the food chain like other organisms and this can have very serious consequences [4].

An energy analyst in International Energy Association (IEA), Molly Walton published a news article with the title of "Commentary: The energy sector should care about wastewater" on 19 November 2018. It is highlighted that the energy consumption of the collection and treatment of wastewater is 4% of total global electricity consumption for today and energy consumption of wastewater treatment (WWT) will reach 680 TWh by the year 2030 [5].

In the light of the environmental laws and environmental awareness of the populations in recent years, there are lots of researches and investigations focused on waste water treatment projects to prevent disasters for all living organisms on the receiving environment such as stream, river, lake, sea [6]. However; for all these kinds of investigations, the equilibrium between "water treated well-enough" and "energy-labor-money consumption" has to be observed [7].

1.2 Motivation of Study

Wastewater treatment is a very complex and detailed process. Various mathematical models have been developed in order to clearly express the process [8]. Processes may vary according to geographical structure, climate, flow rate and wastewater characteristics. In a full scale WWT process operation, mathematical relations between the chemical, physical and biological processes are not easy to model [9]. Obtaining a mathematical model which is exactly "real” is not possible. However "close to real" is sufficient for engineers (Figure1.1).

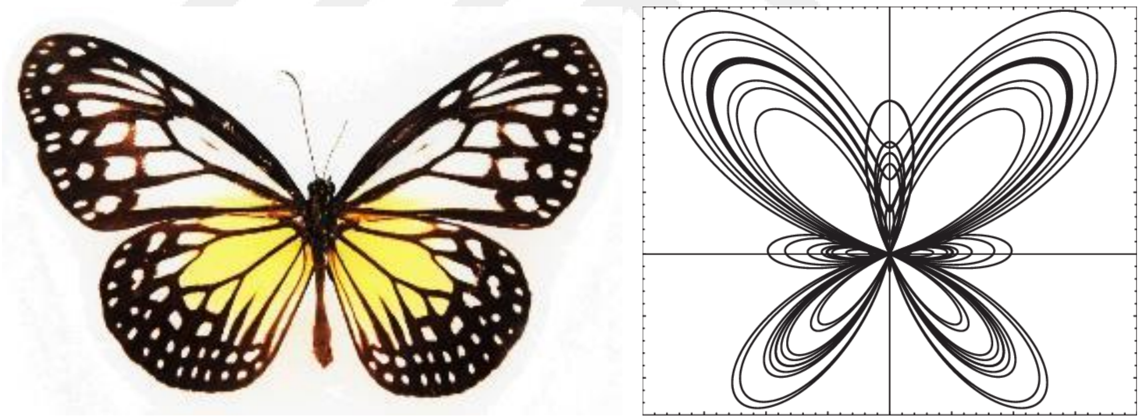

Figure 1.1 A butterfly in reality and a model

The mathematical models which take into account all the physical, chemical and biological factors provide a better understanding of any Wastewater Treatment Plant (WWTP) design [10]. Interdisciplinary studies are carried out for the treatment of wastewater and its removal without damaging the nature. The main target of the design and implementation of WWTP is reduction of biological phosphorus, organic carbon substances and biological nitrogen. The design and implementation procedures consist of several subsystems to achieve biological phosphorus, organic carbon substances and biological nitrogen removal [11].

A WWTP is a combination of complicated processes and it requires execution of several steps for efficacy of WWT including establishment, operation and maintenance. Existing studies focus more on decentralized systems in order to decrease the initial cost despite the fact that decentralized plants may have drawbacks regarding both operation and maintenance steps in WWTP. For efficient operation and maintenance, qualified labor and proper control systems are needed [8]. There has to be an equilibrium between operation and energy consumption, as well as safety and environmental concerns.

1.3 Objectives of Study

In this study, a computer based graphical interface is developed to observe the influent effluent relations for each subsystem in a WWTP, the designed simulator has also become a useful tool for designing new wastewater treatment systems or improve the existing systems or improving the existing systems. Depending on the desired input-output relation of each subsystem of the plant, simulator runs and shows the possible results of each step and process. In order to visually follow the wastewater treatment performance, each subsystem output is graphically observable.

A graphical simulator for pre-design studies to describe the capacity and possible performance of the plant is essential to decrease research and development costs. Energy consumption of a plant, carbon emissions, the quality of the treated water and other outputs are used to optimize the design and implementation of wastewater treatment based on all parameters which have a role in the system. For the actual implementation, the most inexpensive and efficient scenario will be created and treatment performance of the system will be clarified with the aid of this study.

This thesis is focused to overcome the equilibrium problem on the "well-enough treated water" and "energy-labor consumption". Relation between the variables and algorithmic solutions, symbolized by elastic blocks on the simulator of WWT system take into account all variables on a plant via the simulator.

The activated sludge mainly consists of a mixture of wastewater and bacteria population, which is kept moving in water by stirring or aeration [12]. Aeration process is the biggest cause of energy consumption, which constitutes approximately 60% of the total consumed energy in a WWTP [13]. The role of aeration is important for two aspects. First, oxygen is a main component for bacteria and other types of microorganisms to live, grow, and multiply. Second, it supports mixing sludge with the sewage where air is bubbled into the aeration tanks through wastewater that contains dissolved organic substances [14], [15]. The living bacteria consume the dissolved organic materials, which are the pollutants in the waste [6,8,9]. During nitrification, the amount of DO (Dissolved Oxygen) concentration plays a crucial role for the reduction of nitrate (SNO_3) and ammonium, ammonia nitrogen (SNH) concentrations which are more difficult to keep below the legally determined limits [18]. For that reason, DO control and optimization has been a target of a various researches recently [19]–[21]. The aim of the secondary clarifier is to obtain the purified water (effluent) from the activated sludge through sedimentation. The secondary clarifier and the aeration tank together can be considered as a single process from a process control viewpoint [22].

To predict the real behavior of activated sludge process, biological mathematical modeling studies were initialized with Activated Sludge Model 1 (ASM1) [23], in which nitrification, denitrification and carbon oxidation are considered. ASM1 is a model that describes the relation between 13 components in the mixed liquor which are based on: particulate and soluble substrate. In the second model, ASM2 [24], the solution of biological and chemical phosphorus removal are considered. These models are based on Chemical Oxygen Demand (COD) is used to identify organic pollution [25]. ASM2d [26] is an extended model which considers the nitrification capacity of phosphorus accumulating organisms. For ASM3, another essential parameter is also considered, which is the total organic carbon [10], [27]. International Water Association (IWA) summarized the most popular and exact mathematical definitions of biological processes at composed models as ASM1, ASM2, ASM2d, ASM3 [28]. In all of these models, Biological Oxygen Demand (BOD) and COD are the most widely used parameters for characterizing the organic carbon content in wastewater.

Computer-aided design has become part of optimization activities [29]–[31], and computer simulations offer a faster and more efficient way to design WWT processes [32] with extensive mathematical models expressing the processes running in the background [33]–[36]. In this thesis, a mathematical model of unified tank in both aeration and sedimentation process is offered and simulated to investigate the performance of the system [37]. Additionally, in order to improve the performance of an automated unified tank plant, we need to find the optimized parameters in the control loop.

There are many optimization techniques including the metaheuristic approaches that have been widely used recently, many of which have been inspired by biological systems and animals behavior [38]. The spiral path inspired by the motion of feeding humpback whales is called the bubble-net feeding maneuver and it was first mathematically modelled with the purpose of obtaining optimization solutions [39], [40]. The resulting optimization algorithm is named as Whale Optimization Algorithm (WOA) [41]–[44], which is one of the recently developed heuristic optimization methods in use [45]. The WOA method is used in this study to obtain minimized cost for production or maximized efficiency of a unified tank model in aeration system for WWTPs.

1.4 Organization of Thesis

The rest of the paper is organized as follows:

In Section 2, the literature review is presented. Historical development of WWT and WWTP is demonstrated. Recent situation of WWTP reactor technologies is described. Control and simulation studies on WWTPs are demonstrated. The brief information about the WWTPs is also presented on physical, chemical, biological aspects in this section.

In Section 3, defining the bases of optimization the specific optimization steps of WWTP are described and considered with existing WWTP components and the receiving medium. WOA approach is discussed and improvements in aeration and sedimentation are explained for both existing system and UTM concept.

In Section 4, mathematical modelling and modelling strategy is defined and grey box approach is explained. The basic equilibriums for the sub-models are clarified. The aeration and sedimentation tanks in classical approach are described. As a constructive proposal, the Unified Tank Model (UTM) design and modeling with the improvements of proposed physical model structure, both aeration and sedimentation process is clarified.

In Section 5, each subsystem is associated with mathematical expressions presented in section 4. In addition, the relationships of these subsystems with each other are explained. Simulator main algorithm is expressed, design steps are presented. The computer based sub-models are demonstrated.

In Section 6, the Oğuzeli WWTP and influent-effluent characteristics are introduced. Simulation results are given and performances presented in graphical form are discussed for each sub-model. As a case study, simulation tests on existing plant and alternatively modelled UTM design are compared.

Finally, conclusive remarks and recommendations for future studies are presented in Section 7.

CHAPTER II

LITERATURE REVIEW

2.1 Historical Development of WWT and WWTP

People designed and constructed sewers in order to live in a clean environment. Sewers are installed to carry the waste water to the nearest discharging point. Connecting home toilets or bathrooms to the cesspools was another solution for sanitation. Greeks have improved another way to get rid of human waste, they had public toilets and baths. These waste water sources are connected to the collection centers located outside of the city.

The history of sewers has started in Mesopotamian Empire for the storm water drainage (3500 to 2500 BC) [46]. Unfortunately, these collection centers were often overly fertile agricultural areas [46]. In the archaeological studies, four different drainage systems have been found at King Minos' Royal Palace at Knosses (Crete). From 2000 BC, many of the drains of this system are still in use today. At 800 BC Cloaca Maxima, centralized sewer system, was built in Rome [46], [47].

When the population exceeds the self-recovery limits of nature, population has faced another problem; sanitation. Both solid and liquid disposals were thrown out from windows or carried to the rural areas [48]. The streets were periodically washed. Basic principle of the ancient Cloaca Maxima system was carrying this waste surface water to the river. The carried water were proportionally clear [13], However this partial cleaning did not prevent the spread of epidemic diseases such as black plague [14]. In 1596, for Queen Elizabeth, two water closets were built by Sir John Harington [49]. The technical approach to the problem can be expressed as basic modern control principles. This useful invention was not commonly used until 1800, because it was not still usual to connect the toilet pipes to the central constructions [50].

A basic treatment technology was deployed at Craigentinny Meadows in Edinburgh in 1829 [51]. However activated sludge model of WWT based on empirical experience was discovered by George W. Fuller [52] in 1914, shown in Figure 2.1. On the other hand, the date of this discovery is not certain and varies according to the organizations. For IWA and the Kalyuzhnyi S. V. it is 1914 and 1913 respectively, referring to the Ardern and Lockett studies [53],[54]. For Jeanette Brown, former president of the Water Environment Association, the discovery was based on Clark and Gage studies reported in 1913 [52].

The first dynamic model for the activated sludge system was developed from the models discussed in the 1960s for bioreactors [8], [55] (Figure 2.1). The model of activated sludge process proposal studies were unified in 1974 [56]. Different types of reactors such as; Complete Mix Reactor, Batch Reactor, Suspended Reactor, Plug Flow Reactor, the Moving Bed Biofilm Reactor (MBBR) and Membrane Bioreactor (MBR) are used in secondary treatment of WWT process [57]–[60]. MBR technology is an essential recent wastewater treatment technology for operating cost assessment, micro pollutant removal, and sustainability [61], [62]. System details for MBR on both aspects of efficiency and the operational cost were demonstrated [63]. The mathematical modelling studies on MBR technologies demonstrate the advantages and stability of operation [64], [65].

Figure 2.1 A general view of WWTP

The fill and draw system in the aeration process of a WWTP, called Sequential Batch Reactor (SBR), was first designed and used at Corpus Christi, Texas in 1969 for large-scale industrial WWT [25], [66], [67] (Figure 2.2). With the improvements in computers and electronically controlled valves, SBR has been dramatically improved and widely used in the biological treatment of industrial and domestic wastewater containing organic compounds in recent decades [46], [49], [67]. SBR plants which are properly controlled have many advantages making them a competitive alternative to classical activated sludge systems [52], [68], [69]. The SBR process saves more than 60% of the operating costs compared with a conventional activated sludge process, with the capacity to treat a similar amount of wastewater in a cycle [67].

Figure 2.2 A general view of SBR type WWTP

2.2 Development of WWTP Control and Simulations

Over the last 50 years, from 1970's, the development on control structures have rapidly developed [46]. The solutions improved in 1970s on the WWTP still solve the main process control problems [70]. At the end of 1970s, electrically controlled equipment such as valves were introduced along with electronic computers in industry.

In late 1980s, personal computers (PCs) started to be used commonly. The concept of industrial computers evolved to more visualized types. This improvement led the researchers to develop more visualized computer models based on mathematical principles of the treatment processes [71]. The most popular type of treatment system, activated sludge process is the main content of this models; in these years the anaerobic baffled reactor for WWT has been just developed [72]. Since the early 1980s, the baffled reactor for WWT has some additional advantages over well-designed systems such as the up flow anaerobic sludge blanket and the anaerobic filter.

During this tenure, depending on heightened environmental concerns, the other wastewater research categories such as; Physical, Biological and Chemical have been revised using mathematical approaches. Computer based mathematical modeling approaches make systems more efficient and realistic and thus decrease the operating cost on treatment systems for both domestic and industrial WWT [72], [73].

The last generation of the waste water treatment system researches is simulations. Models of the treatments are re-created in simulations in order to observe the operation of the system in electronic medium. The most prominent simulation studies are of the last two decades is International Association on Water Pollution Research and Control's (IAWPRC) model based on COD [74].

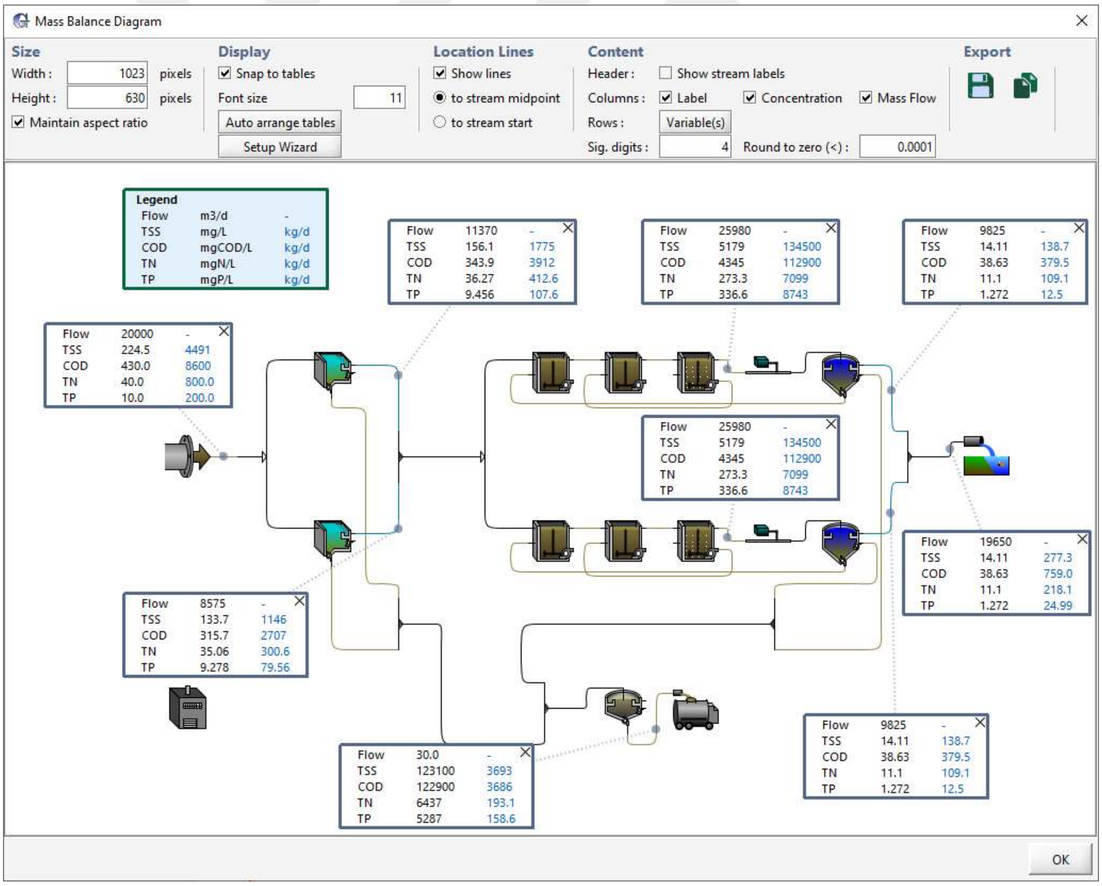

Figure 2.3 A schematic presentation of a system on GPS-X [36]

These simulations are essential to observe the theoretical system behavior [46]. Weather conditions and other outside factors, such as dry, stormy and rainy weather conditions, affect the treatment process [11],[75],[76]. These variables and disturbances are also taken into account in such updated studies, predictive control concept [77]–[79]. Sewer systems, WWTPs and receiving waters are also mathematically modeled and available on recent simulators [11], [80]. Because of the elasticity and ease of use, computer is frequently used for both simulators and mathematical modeling on the WWTPs and other related sub-systems [11], [27], [73], [77], [81]–[85].

STOAT is a PC based modeling software which simulates dynamically the performance of WWTPs. The tools of the software enables simulating individual treatment steps for optimizing the process, influent characteristics, treatment capacity or operating conditions on different process (Figure 2.4-2.5). Various components of treatment process are modeled such as; primary tanks, sedimentation tanks, oxidation pool, etc [86].

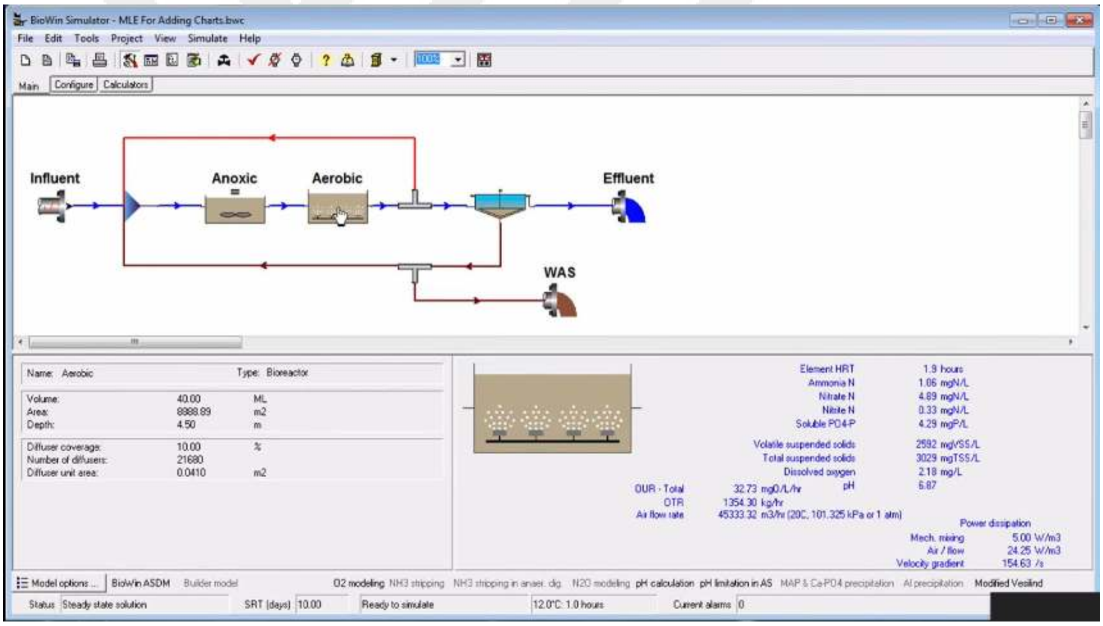

Figure 2.4 A schematic presentation of a system on BioWin [87]

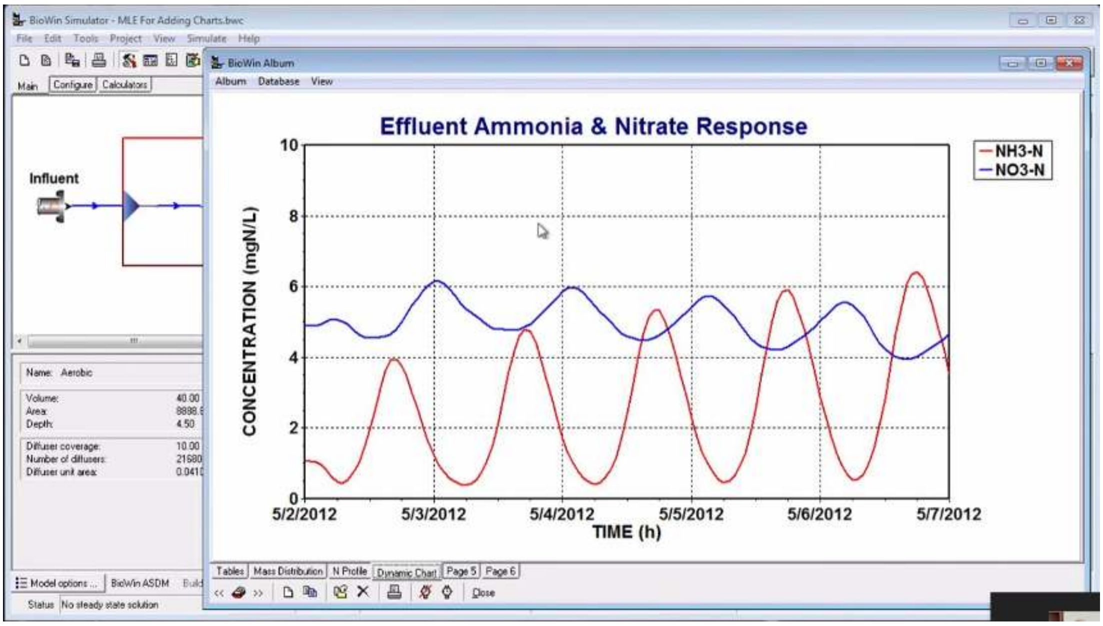

Figure 2.5 A graphical presentation of a system on BioWin [87]

WEST is a platform for dynamic modeling and simulation of water quality systems. The concept of this software also includes rivers sewers and urban catchments in addition to WWTP. There are blocks in internal library to control system. WEST includes an important development that allows for integration of Supervisory Control and Data Acquisition (SCADA) to WWTP. "Decision support system" is an essential feature to assist the operator in plant management. WEST is a completely open modeling environment for the implementation of customized models through a model editor and block editor. With such subsystems which are useful to optimization, the optimization tool enables flexible and open model structure. The optimization toolbox is useful to performance evaluation and cost minimization [88].

WEST is a pioneer to combining fast integration to the existing systems and allows linking the software with SCADA systems. Input and output control is interactively available to visualize simulation outputs (Figure 2.6 and 2.7).

Figure 2.6 A schematic presentation of a system on WEST[34]

Figure 2.7 Graphical presentations of ammonia, nitrate and total P changes during the process

Figure 2.7 shows the sample visuals of WEST. The change of ammonia, nitrate and total P is observable during all of the process steps. The continuous signal which is provided by this experimental work can be compared with the exact field values on measurement points as a discrete value [89]. The mathematical approach is to obtain the error function for an optimal operation [88].

As a result, Graphical Simulators for WWTP include several aspects of both environmental and efficiency concerns [81]. These usually contain extended database and libraries which are used to define the process models of WWTP. The distinctly performed simulations for each component (block - process) of a plant are available to check the utility of any proposed treatment system [90]. Appropriate elastic process unit blocks are composed for the configuration of the system. The model parameters which run in the system can be updated via pop-up windows [11]. There are several software packages used for both static and dynamic conditions, such as; ATV-DVWK-A 131E, GPS-X, Aqua Designer, ARA-BER, DENICOMP, Denika / Denika plus, Denni, AQUASIM, Arasim, ASIM, DENISIM, EFOR ApS, SASSPRO [10] [91]. Commercial and academic studies on SIMBA, GPS-X, WEST, STOAT and SUMO are more stable and realistic for WWTP.

Based on literature review, the mathematical approach has guided to develop a new Graphical Simulator for WWTP Design. computer applications are available to solve the problem during the design and operation procedures [92].

2.3 Brief Information of Process

The process of WWT starts with collecting domestic and industrial wastewater. Although industrial wastewater flow rate is small for rural areas, compared with domestic wastewater; pollutants in industrial wastewater contain more hazardous and complex components [97], [98]. Usually this is an undesirable situation which will have negative effects on urban WWTPs [95]. In order to operate a treatment plant efficiently, the measurements on the water clearly obtained. Domestic and industrial components of wastewater, various chemicals and the desired output to the receiving environment are seriously analyzed [27].

The WWT process is summarized in four main categories; Physical, Chemical, Biological and Advanced Biological Treatment. After these processes, sludge dewatering is another step which is not directly related with water treatment. All the usages and purposes of these stages are examined, respectively, as shown in Figure 2.8 below.

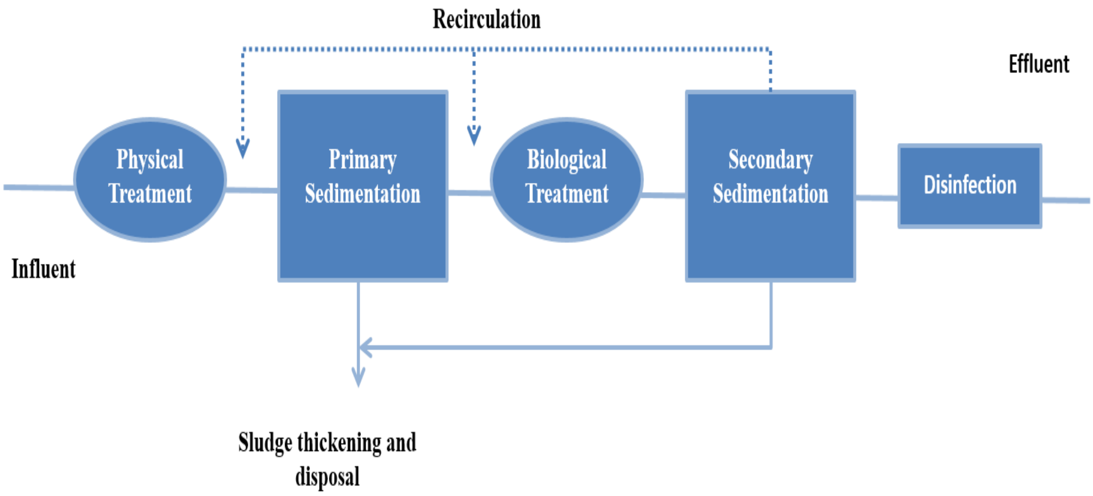

Figure 2.8 Schematic presentation of the WWT plant

2.3.1 Physical Treatment

Physical treatment of water, floatable solids of various sizes, includes operations to remove organic and inorganic dissolved substances [96]. Physical treatment units are screening, mixing and flocculation, grit removal, and primary sedimentation [97]–[99].

Figure 2.9 Electro mechanic screening system of WWT plant

The main function of primary sedimentation tank is to filter organic particulate matter so it does not pass to the aeration tank. The settled particles are gathered and brought to treat the sludge. Settling capacity depends on the tank hold time which is calculated by both empirical and deterministic methods. The empirical methods monitor the settling output by means of a practical relationship between the concentration of inflow and the time of retention, to be calculated from observations. The actual physical process of sedimentation is mathematically described in Chapter IV. Deterministic approaches detail the process of physical settlement similar to the secondary sedimentation tank.

Different approaches are available depending on the degree of modelling of the flow and transport process. Continuously stirred reactor tank (CSTR) models (Figure2.10) use basic equations for the mass balance [100][101]. The liquid in the tanks is continuously mixed during the aerobic and anaerobic phases in order to prevent undesirable sedimentation. The hydrodynamic impact on collection tanks are clearly expressed via mathematical formulations. The mathematical formulations of the flow and transport cycle are used by hydrodynamic models which are demonstrated in Chapter IV [102].

Primary treatment is a part of physical treatment which means the domestic wastewater treatment involves physical or chemical primary processes. At this stage, the sedimentation of suspended solids which contains measured organic matter called as BOD5. BOD5 is used to define biochemical oxygen demand which is reduced by at least 20%. In the same stage, total suspended solids (TSS) is also reduced by at least 50% [99], [103], [104].

There are several treatment options for wastewater which can be classified into groups of processes. The classifications of these groups are based on their functions and complexity. Preliminary treatment dealing with debris and solid material which are simple processes. Preliminary treatment is intended to eliminate certain components which are easily separable. Typically this is achieved by inspection by bar screens and removal of the grit. This removal is necessary to improve the efficacy of whole subsequent treatment processes and equipment.

Primary Treatment is focused to removal of settlement solids. Settling of the solid material in wastewater reduces large amounts of the polluting charge. It can reduce BOD by as much as 40%. Screening, grit chamber and primary sedimentation tanks are some components of primary treatment [7].

2.3.2 Chemical Treatment

Dissolved or suspending water while changing the physical state of a substance applied to the purification process to ensure the deposition. The chemical treatment, chemicals suitable pH value of the wastewater (coagulants, polyelectrolyte and so on.) Adding the result of the desired substance precipitated is separated by precipitation from water slurry [105]–[107].

Requirements such as the elimination of heavy metals and phosphorus, are given for chemical treatment of suspended solids, COD, BOD. Chemical treatment systems can be constructed in concrete and steel [73].

2.3.3 Biological Treatment

Change and conversion is a part of nature. For biological treatment process, pollutants in the wastewater are transformed to water and carbon dioxide by living organisms, which involves 85% water. The conversion to the carbon dioxide of dissolved organic contaminants in the wastewater produces treated water. During the sedimentation process microorganisms sink to the bottom layers from surface layers. [108]–[110].

All biological processes performed in the aeration and secondary sedimentation tank are called as secondary treatment. By the secondary treatment, the measured organic matter, called as BOD5, is decreased between 70 to 90%. Similarly COD is reduced at least 75% via secondary treatment.

Depending on the influent characteristics, TSS increases from 60% to 90%. Aeration (Figure 2.10-2.11) and sedimentation tanks (Figure 2.12) are main units for providing conditions for growth of heterotrophic organisms which degrade organic materials in water. For secondary treatment, other process units which are commonly used are: trickling filters, stabilization ponds and anaerobic reactors [104].

Figure 2.10 A general view of oxidation ditch

Figure 2.11 Fuchs type aeration

Figure 2.12 Secondary sedimentation tank

The secondary sedimentation tank and the aeration tank (Figure 2.13) are known as one process group. The secondary clarifier's main function is to split the activated sludge from the filtered water produced during sedimentation. Like the primary clarifier the activated sludge consists mainly of flocks of mud. Sludge is thickened and then redirected partially to the drainage tank.

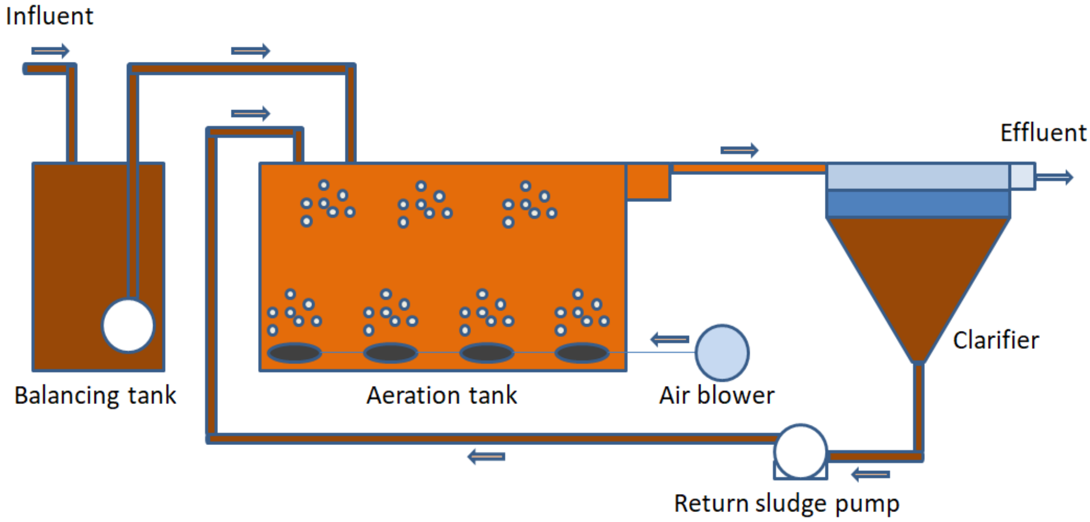

Figure 2.13 Schematic diagram of activated sludge treatment process [10]

The secondary sedimentation is essential to provide desired effluent characteristics. At the end of the sedimentation process retention time must be able to be calculated based on desired effluent concentrations.

There is a ratio between influent and effluent flow rate. In case of excessive influent flow rate, the treatment process must continue via increased effluent flow rate. There are some multidimensional models which take into account several equations on mass, energy, effluent water quality, etc. However, empirical models generally based on operational experience without exact calculations on the sedimentation process are considered with one dimensional models.

Although the CSTR is a useful assumption to restrict sedimentation in retention time interval, the tank shape and dimensions are also required for detailed calculations on both sedimentation and aeration tanks. Moreover, settling speed and sinking behavior which are other functions related with aeration are essential to determine retention time. For such cases, neither the multidimensional models nor the empirical models are not adequate for real implementation. This is an optimization problem mentioned in Section 4.4, discussed in UTM concept.

The Taka´cs et al model. (1991) solves the calibration problem for special cases using a double-exponential settling function with four parameters. Since it is not easy to measure extensive values on the plant, another two component (sludge index and concentration of solids in the effluent) model from Otterpohl & Freund (1992) is developed [101]. In Section 4.4.1, two more models (Bürger-Diehl and Godunov flux model) are mathematically described and used for the problem formulations.

2.4.4 Advanced WWT

Advanced WWT, aiming to achieve higher quality treated water for specific uses (such as irrigation) requires removing the nitrogen and phosphorus in the wastewater at a higher rate [107].

For this purpose, there are ammonium ions contained in the wastewater prior to nitrite nitrogen in the nitrification stage by means of bacteria and then converted to nitrate. Then water is removed as nitrogen gas under anoxic conditions in the de-nitrification step [102], [110].

Chemical and biological methods to eliminate the phosphorus compounds are used separately or together. Biological methods with phosphorus treatment is achieved by taking phosphate by microorganisms during biological treatment [49], [111], [82], [112].

As a summary, the modern WWTPs are complex systems involving different disciplines such as physics, chemistry, biology, computer sciences and control. Controlling the equipment in external disturbances [49], [82], [90] needs several feedback loops [70], [85], [113]. The daily and seasonal fluctuations on the water characteristic which involve many physical, chemical and biological parameters [11] require control via dynamic equipment and computers [49]. The dynamic equipment and computer aided control systems like SCADA are widely used for efficient operations in WWTPs.

2.4.5 Disinfection and Release

A final stage in treatment includes the consistency of the effluent until it is discharged into the receiving area. Nitrogen (N) and Phosphorous (P) removal is usually applied to the secondary treatment within the cycle. Nutrient removal is accomplished using either chemical or biological processes.

Specific efficiencies in removals are above 80%. Other tertiary treatments such as sand filtration and disinfection always end the process and are also referred to as effluent polishing [104].

CHAPTER III

OPTIMIZATION

A graphical simulator for pre-design studies to describe the capacity of the plant, systems is essential to decrease investigation and operation costs. In each process, the block performance depending on the related wastewater characteristics is observable. Energy consumption of a plant, carbon emissions, the quality of treated water and other outputs (as shown in Figure 3.1) are optimized based on all parameters which have a role in a treatment system [78].

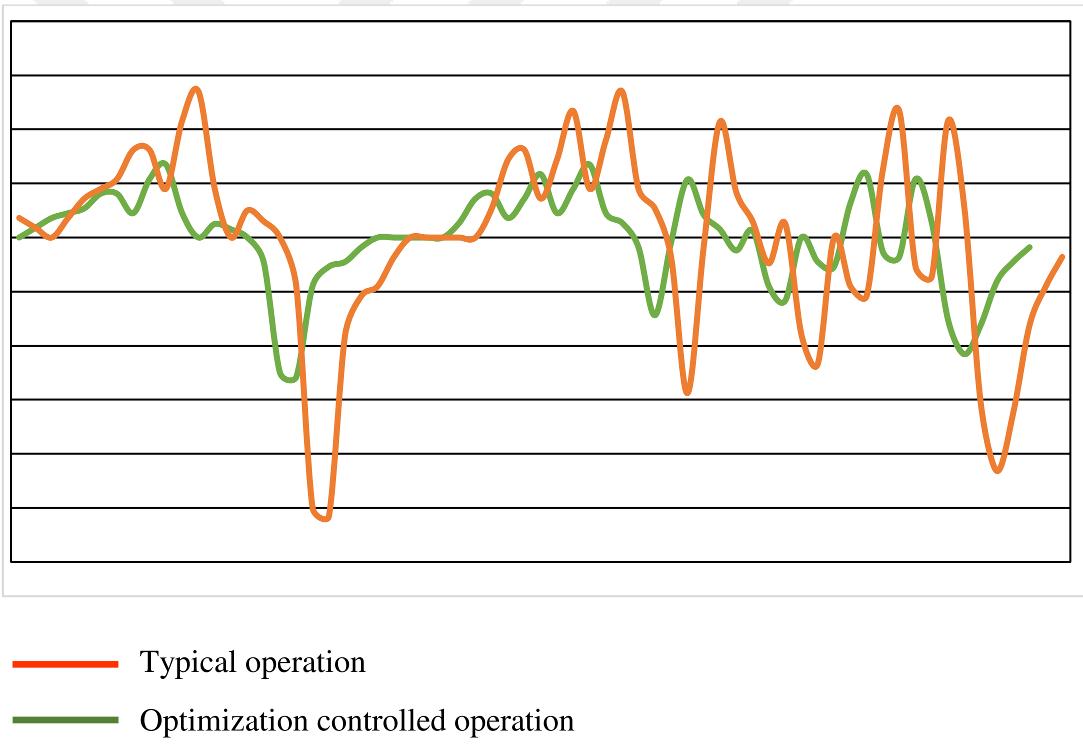

Figure 3.1 Typical-optimization controlled operation comparison

For designing a new system, the simulations of the project for different points such as; metal filter, sand filter, precipitation pool etc. are observed before installation. For real implementation, the most economical and optimized scenarios are obtained with the help of this study.

The following optimization process steps were used for each case study:

The system boundaries and the related interfaces which are outside of the system are defined.

Inputs are defined: controlled variables (also known as degrees of freedom) and disturbances. The controlled variables in a drainage system are typically correlated with the pipe sizes, slope, depth of cover, volume of storage etc. One of a drainage system's primary disturbances is precipitation.

Time scale is defined: The time is highly dependent upon the configuration of the system. The time of concentration is important in a drainage design for selecting the precipitation event used to evaluate the alternative solutions. The time scale may be in the order of hours. However, if there is also interest in reducing the impacts of pollution in the receiving system, the time scale may be increased to the order of days or even weeks.

The status of the system is defined: Defines the variables of the machine state, which in turn specifies the output variables to be optimized. Within a drainage system, the state variables are correlated with water quantities (e.g. flows, flood volumes) and/or water quality parameters (e.g. organic matter, suspended solids).

Decision variables (degrees of freedom) are defined: Defines variables for the decision (degrees of freedom). These are design variables or set points for controls. We have to have an effect on goals. Degrees of freedom (n) describe the decision variables in n-dimensional space.

Cost functions are defined: Cost functions must be capable of reflecting the consequences of various changes in decision variables. Principally, defining an observable predictor is initially aimed. The indicator may be the modelling software state variables (e.g. flood volume) or may be estimated as a function of the decision variables (e.g. pipe network cost).there are three types of performance indicators: water quantity, water quality and cost. There are two types of cost metrics; investigation and the operating cost. Typically the cost of the investment is not part of the modeling but an alternative solution such as UTM [37] may be proposed depending on the existing operation conditions. The operational costs are based on electricity (for water pumping and recycling and compressing air), chemical additives and labor. Total Efficiency Block (Figure 5.8) presents a result on operation costs for both existing system and optimum design.

Constraints are defined: Describing the limits to present a feasible solution. For optimization procedures, the constraints can be classified in two main categories:

1) System constraints: ratios of mass and energy, flow levels and concentrations etc.
2) Restrictions on the equipment: volumes, maximum and minimum flow rates, some equipment may only be on-off.

Apart from these two constraints; the software and modelling limits are considered as restrictions on process and equipment.

Essentially, optimization is everywhere, from computer design to economics and from holiday planning to internet search engines. Money, resources and time are constantly limited, the optimal use of these available resources is crucial. [114] Real-world optimization problems are highly nonlinear and multimodal. Generally, finding an optimal solution or even sub-optimal solutions is not an easy task under various complex constraints and different objectives which are conflicting.

There are many optimization algorithms that, depending on the objective and the characteristics, can be categorized in many ways.

The algorithm decides targeted functions which involve the parameters that control the criteria on: population size, number of generations, probability of mating, probability of mutation and stopping criteria etc. Initial population selection depends the optimization sub-system process to obtain the best solution for the systems.

3.1 Whale Optimization Algorithm

Meta-heuristic optimization algorithms such as WOA, Particle Swarm Optimization (PSO) or Genetic Algorithm (GA) which are influenced by nature have some advantages; they are based on simple concepts and easy to implement, gradient information is not required, local optima can be neglected [38], [115], [116]. Moreover, the solutions of the problems for different disciplines become simpler. Significant optimization has been achieved with the particle swarm optimization technique used for the anaerobic digestion, which is a complex model [117].

Whale Optimization Algorithm was proposed by Seyedali Mirjalili and Andrew Lewi [40] in 2016 for several optimization problems [41]–[44]. In this study, it is aimed to increase the efficiency of wastewater treatment plants aeration system with WOA.

This study is focused on the benchmark system developed for the process of biological reactions and solid–liquid separation that occur periodically. The process is optimized by WOA which is inspired by bubble-net feeding behavior, [39], [40] the hunting behavior of whales as they hunt for the nutrients close to the surface creating distinctive bubbles along an Archimedean path as shown in Figure 3.2

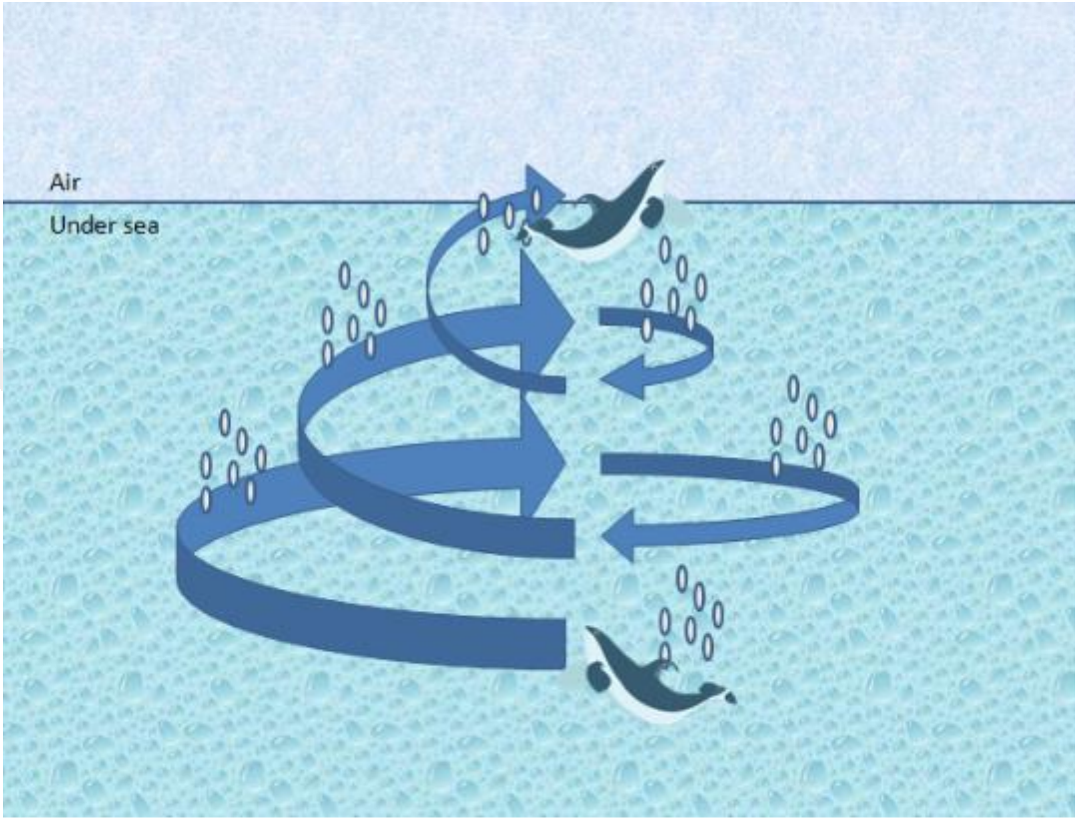

Figure 3.2 Whales' bubble-net feeding behavior

Bubble-net feeding behavior is simulated as a spiral movement of the whales around their prey [43]. WOA algorithm presents best candidate solution which is close to the optimum. There are two phases in this algorithm; prey and encircling [42]. This behavior is represented by the following equations. Whales moves around the prey as [40]:

$$\overrightarrow{X_w}(t+1) = \vec{D}e^{bl}\cos(2\pi l) + \overrightarrow{X_p} \qquad (3.1)$$

where $\vec{D} = \left|\overrightarrow{X_p}(t) - \overrightarrow{X_w}(t)\right|$ is the distance between a whale and prey $\overrightarrow{X_w}(t)$ and $\overrightarrow{X_p}(t)$ respectively. The whales update their positions based on the best location named as encircling behavior as follows:

$$\vec{D} = \left| \vec{C} \bullet \overrightarrow{X_p}(t) - \overrightarrow{X_w}(t) \right| \tag{3.2}$$

$$\overrightarrow{X_w}(t+1) = \overrightarrow{X_p}(t) - \vec{A} \bullet \vec{D} \tag{3.3}$$

where A and C are coefficient vectors that are computed as;

$$\vec{C}=2\vec{r} \tag{3.4}$$

$$\vec{A}=2\vec{\alpha} \bullet \vec{r} - \vec{\alpha} \tag{3.5}$$

The probability assumption is 50% between the movement around the prey in shrinking circles or position updating randomly which is modelled as;

$$X_w(t+1) = \begin{cases} \vec{D}\, e^{bl} \cos(2\pi l) + \overrightarrow{X_p}(t) & \text{if } pr \geq 0{,}5 \\ \overrightarrow{X_p}(t) - \vec{A} \bullet \vec{D} & \text{if } pr < 0{,}5 \end{cases} \tag{3.6}$$

Note that " • " represents the dot product operator of two vectors in (3.2-3.6).

CHAPTER IV

MATHEMATICAL MODELING

Human beings have developed many innovations that make life easier with inspiration from nature. Although mathematics is an important way to understand the nature; mathematical definition of many complex systems is still not fully understood. In such cases, the "grey and black box model" is used to obtain the most realistic models. The grey and black box model concept is used when the mathematical expression of the system cannot be clearly revealed. Black box model is useful to obtain a solution which is an under operating conditions system [118] (Figure 4.1).

Figure 4.1 Grey box modeling

Mathematical model is used to represent how a real system works. Models are very simple or very complex depending on both the system mechanism and system requirements [84]. For any process, first it’s needed to define the functional specifications and the objectives of the process (purpose, accuracy, boundaries, time scale etc.). Defining the process is important part of the modeling in order to understand what is needed and how much accuracy is enough [85].

After clarification of the functional specifications and the objectives of the process, the model type should be defined. (Mechanistic vs Black-Box (I/O or Autoregressive Moving Average eXogenous (ARMAX)), deterministic vs stochastic, continuous vs discrete, distributed vs lumped, time domain vs frequency domain) [119]. As a next step, depending on the model type, the model is developed, scaled (e.g. for dissolved oxygen dynamics seconds scaled, for biomass growth days and weeks scaled.) [75]. The model is developed, verified and calibrated until reaching the desired accuracy (Figure 4.2).

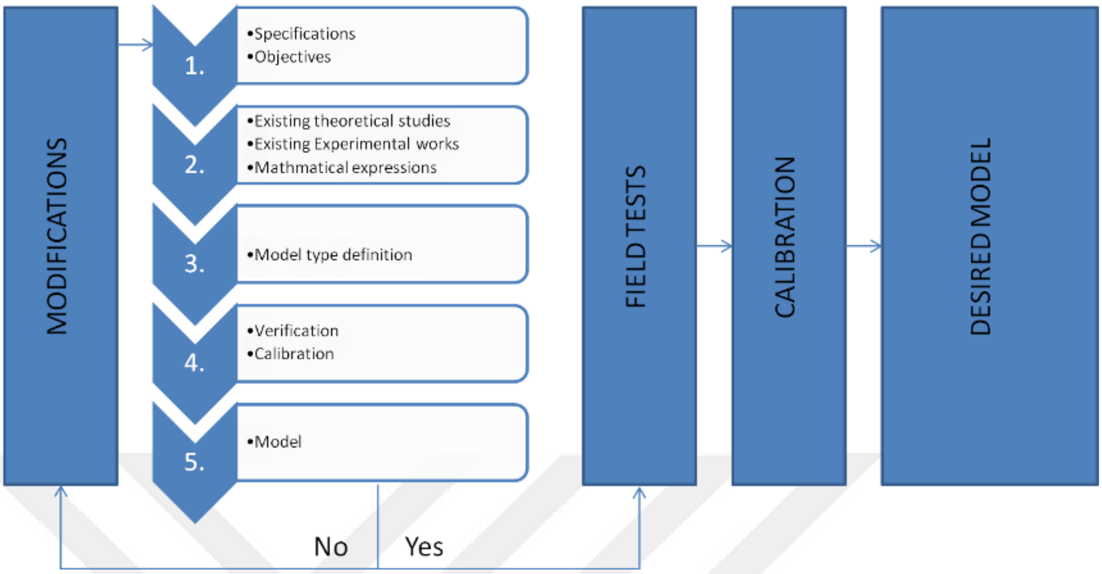

Figure 4.2 Modeling strategy algorithm [120]

4.1 Biomass and Substrate Equilibrium

WWTPs are fundamentally hydraulic systems. The main governing equation for any hydraulic system is the volume balance equation, which is formulated in terms of the difference between the charge and the discharge as shown in Figure 4.3.

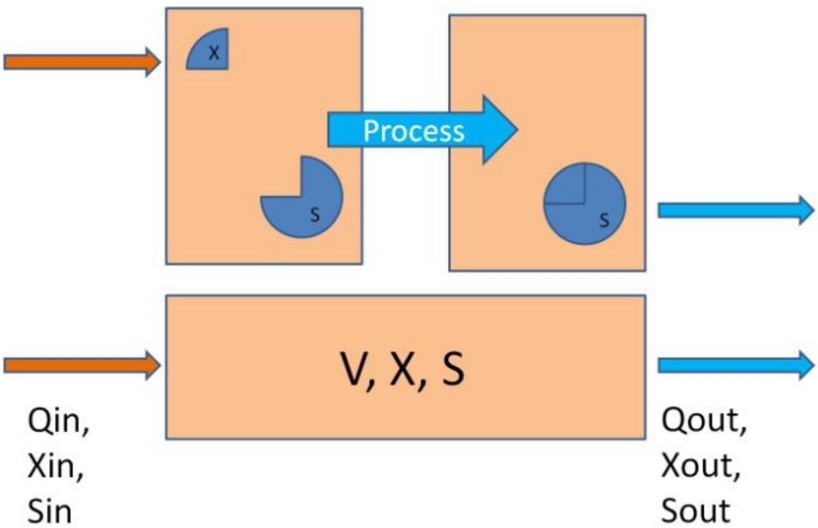

Figure 4.3 WWT flow diagram

The activated sludge models that focus on food-microorganism ratio is given in (4.1) [10], [16] ;

$$\frac{F}{M} = \frac{QS_{in} - QS_{out}}{XV} \tag{4.1}$$

The activated-sludge process is aimed at removing substances that have a demand for oxygen from the system. The metabolic reactions of synthesis-respiration and nitrification are performed by the microorganisms [17], [100].

The activated sludge model is focused on biomass concentration and growth rate of the microbes [16]. The schematic flow diagrams in Figure 4.4 show mass-balance equations. All designs of biological treatment reactors are based on biomass-substrate equilibrium [10]. As part of the whole concept, two state variable system is defined below.

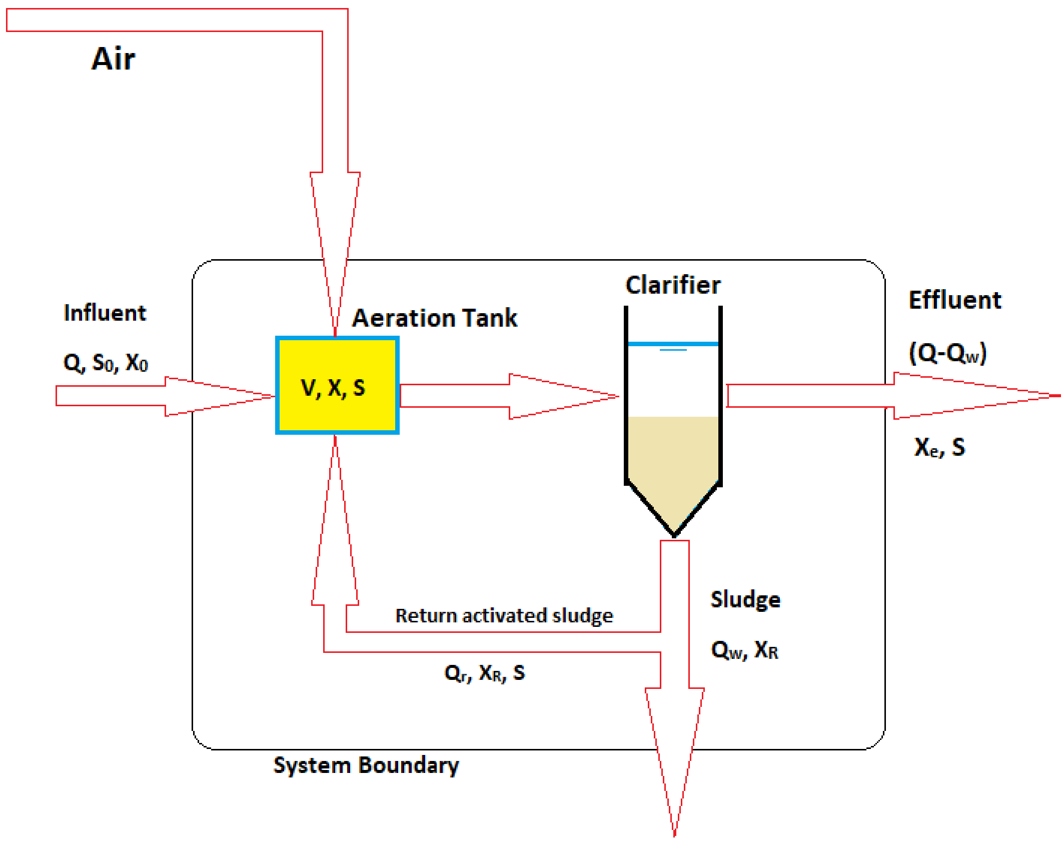

Figure 4.4 Schematic diagram of activated sludge treatment process with model nomenclature with wasting from the sludge return line [10]

$$\frac{dX}{dt} = \mu(S)X - bX \tag{4.2}$$

$$\frac{dS}{dt} = -\frac{1}{Y}\mu(S)X \tag{4.3}$$

$$\mu(S) = \frac{\hat{\mu}S}{K_s + S} \tag{4.4}$$

where S is the substrate and X is the biomass, which are both assumed to be measurable. The system which involves 4 parameters (K_s, μ, b,Y) is globally identifiable.

Let X_0=X(0); S_0= S(0)

$$X'(0) = \frac{\hat{\mu}S}{K_s + S}X_0 - bX_0 = X_1 \tag{4.5}$$

$$S'(0) = -\frac{1}{Y}\frac{\hat{\mu}S_0}{K_s + S_0}X_0 = S_1 \tag{4.6}$$

$$\mu = \frac{\hat{\mu}S_0}{K_s + S_0} \tag{4.7}$$

$$X_1 = (\mu - b)X_0 \tag{4.8}$$

$$S_1 = -\frac{\mu}{Y}X_0 \tag{4.9}$$

Take the first-order Taylor series expansion of Eq. (4.2) and (4.3) at time t=0

$$X''(0) = (\mu - b)X_1 + \frac{\mu K_s X_0 S_1}{(K_s + S_0)S_0} = X_2 \tag{4.10}$$

$$S''(0) = -\frac{\mu}{Y}(X_1 + \frac{\mu K_s X_0 S_1}{(K_s + S_0)S_0}) = S_2 \tag{4.11}$$

Solve (4.8), (4.9), (4.10) and (4.11) for K_s, μ, b, Y.

$$K_s = \frac{S_2 S_0^2 X_0 - S_1 S_0^2 X_1}{S_1^2 X_0 - S_2 S_0 X_0 + S_1 S_0 X_1} \tag{4.12}$$

$$\mu = \frac{X_2 X_0 S_1 - X_1^2 S_1}{S_2 X_0^2 - S_1 X_1 X_0} \tag{4.13}$$

$$\hat{\mu} = \frac{(X_2 X_0 S_1 - X_1^2 S_1)(K_s + S_0)}{S_2 S_0 X_0^2 - S_1 S_0 X_1 X_0} \tag{4.14}$$

$$b = \frac{S_1X_2 - S_2X_1}{S_2X_0 - S_1X_1} \quad (4.15)$$

$$Y = \frac{X_1^2 - X_1X_0}{S_2X_0 - S_1X_1} \quad (4.16)$$

According to the mathematical approach, the parameters are identifiable. In case of any noise-corrupted measurements, the parameters are not uniquely identifiable.

4.2 Modeling of a Single Substrate System

For any hydraulic system, the volume is equal to the difference between the charge (accumulation) and the discharge (reaction), presented in Figure 4.3.

Biomass (X_H):

$$QX_{H,in} - QX_{H,out} = \frac{d(VX_H)}{dt} - r_H V \quad (4.17)$$

$$\frac{dX_H}{dt} = \hat{\mu}\left(\frac{S_S}{K_s + S_S}\right)X_H - \frac{X_H}{\theta} \quad (4.18)$$

$$r_{X_H} = \hat{\mu}(\frac{S_S}{K_s + S_S})X_H \quad (4.19)$$

$$X_{H,in} = 0 \quad (4.20)$$

CSTR---------> $X_{H,out} = X_H$

Substrate (S_s):

$$QS_{S,in} - QS_{S,out} = \frac{d(VS_S)}{dt} - r_S V \quad (4.21)$$

$$\frac{dS_s}{dt} = \frac{1}{\theta}((S_{S,in} - S_S)X_H - \frac{1}{Y_H}\hat{\mu}(\frac{S_S}{K_s + S_S}))X_H \quad (4.22)$$

$$r_{S_s} = -\frac{1}{Y_H}\hat{\mu}(\frac{S_S}{K_s + S_S})X_H \quad (4.23)$$

CSTR--------->$S_{S,out} = S_S$

Table 4.1 Two-State / One Process model in Petersen matrix format [49]

PROCESS	COMPONENTS		PROCESS RATE KINETICS
	Substrate	Biomass	
Aerobic heterotrophic growth	$-\frac{1}{Y_H}$	1	$\hat{\mu}\left(\frac{S_S}{K_s + S_S}\right)X_H$

4.3 Activated Sludge Model

IAWPRC initiated a mathematical modeling study on activated sludge process in 1982 [8]. The Activated Sludge Model No. 1 (ASM1) was introduced in 1987 as IAWQ Model no. 1 (ASM1). IAWQ Task Group on Activated Sludge Modeling defined a simple model consisting of 8 processes, 13 state variables or components and 19 parameters [23] (Table 4.2).

Table 4.2 Process variables and parameters in ASM1 [49]

$i \rightarrow$ / $j \downarrow$	1 S_I	2 S_S	3 X_I	4 X_S	5 X_{BH}	6 X_{BA}	7 X_P	8 S_O	9 S_{NO}	10 S_{NH}	11 S_{ND}	12 X_{ND}	13 S_{ALK}	Reaction
ρ_1		$-\frac{1}{Y_H}$			1			$-\frac{1-Y_H}{Y_H}$		$-i_{XB}$			$-\frac{i_{XB}}{14}$	$\mu_H \frac{S_S}{K_S+S_S} \frac{S_O}{K_{OH}+S_O} X_{BH}$
ρ_2		$-\frac{1}{Y_H}$			1				$-\frac{1-Y_H}{2.86Y_H}$	$-i_{XB}$			$\frac{1-Y_H}{14 \cdot 2.86Y_H} - \frac{i_{XB}}{14}$	$\mu_H \frac{S_S}{K_S+S_S} \frac{K_{OH}}{K_{OH}+S_O} \frac{S_{NO}}{K_{NO}+S_{NO}} \eta_g X_{BH}$
ρ_3						1		$-\frac{4.57-Y_A}{Y_A}$	$\frac{1}{Y_A}$	$-i_{XB} - \frac{1}{Y_A}$			$-\frac{i_{XB}}{14} - \frac{1}{7Y_A}$	$\mu_A \frac{S_{NH}}{K_{NH}+S_{NH}} \frac{S_O}{K_{OA}+S_O} X_{BA}$
ρ_4				$1-f_P$	-1		f_P					$i_{XB} - f_P i_{XP}$		$b_H X_{BH}$
ρ_5				$1-f_P$		-1	f_P					$i_{XB} - f_P i_{XP}$		$b_A X_{BA}$
ρ_6										1	-1		$\frac{1}{14}$	$k_a S_{ND} X_{BH}$
ρ_7		1		-1										$k_h \frac{X_S/X_{BH}}{K_X+X_S/X_{BH}} [\frac{S_O}{K_{OH}+S_O} + \eta_h \frac{K_{OH}}{K_{OH}+S_O} \frac{S_{NO}}{K_{OH}+S_{NO}}] X_{BH}$
ρ_8											1	-1		$\rho_7(X_{ND}/X_S)$

The model was enhanced as ASM1, ASM2 and ASM3 several times to address specific shortcomings [23]. Models are concerned with carbon oxidation, nitrification and denitrification. ASM2 also contributes to the solution of biological and chemical phosphorus removal. The models are based on COD units (use COD to identify organic pollution). For characterizing the organic carbon content in wastewater, the parameters BOD and COD are widely used. For ASM3, another essential parameter is TOC [10].

$$\mathrm{COD} = S_S + \alpha h X_S \tag{4.24}$$

Shown in Eq. (4.24) αh is a conversion factor that is required because the units of soluble substrate (S_S) differ from that of biodegradable particulate substrate (X_S)

Mathematical models are used to represent mechanisms depending on the system requirements [84]. For example to obtain higher quality treated water (such as for use in irrigation) the nitrogen and phosphorus in the wastewater must be removed at a higher rate [107]. The ammonium ions exist in the wastewater turns nitrite nitrogen in the nitrification stage via bacteria and then finally converted to nitrate. Then water is removed as nitrogen gas under anoxic conditions in the de-nitrification step [102], [110].

Chemical and biological methods to eliminate the phosphorus compounds are used separately or together. Biological methods with phosphorus treatment involve removing phosphate by microorganisms during biological treatment [49], [111]. The correlations between the 8 processes, 13 state variables and 19 parameters of ASM (Table 4.2) is schematized in Figure 4.5.

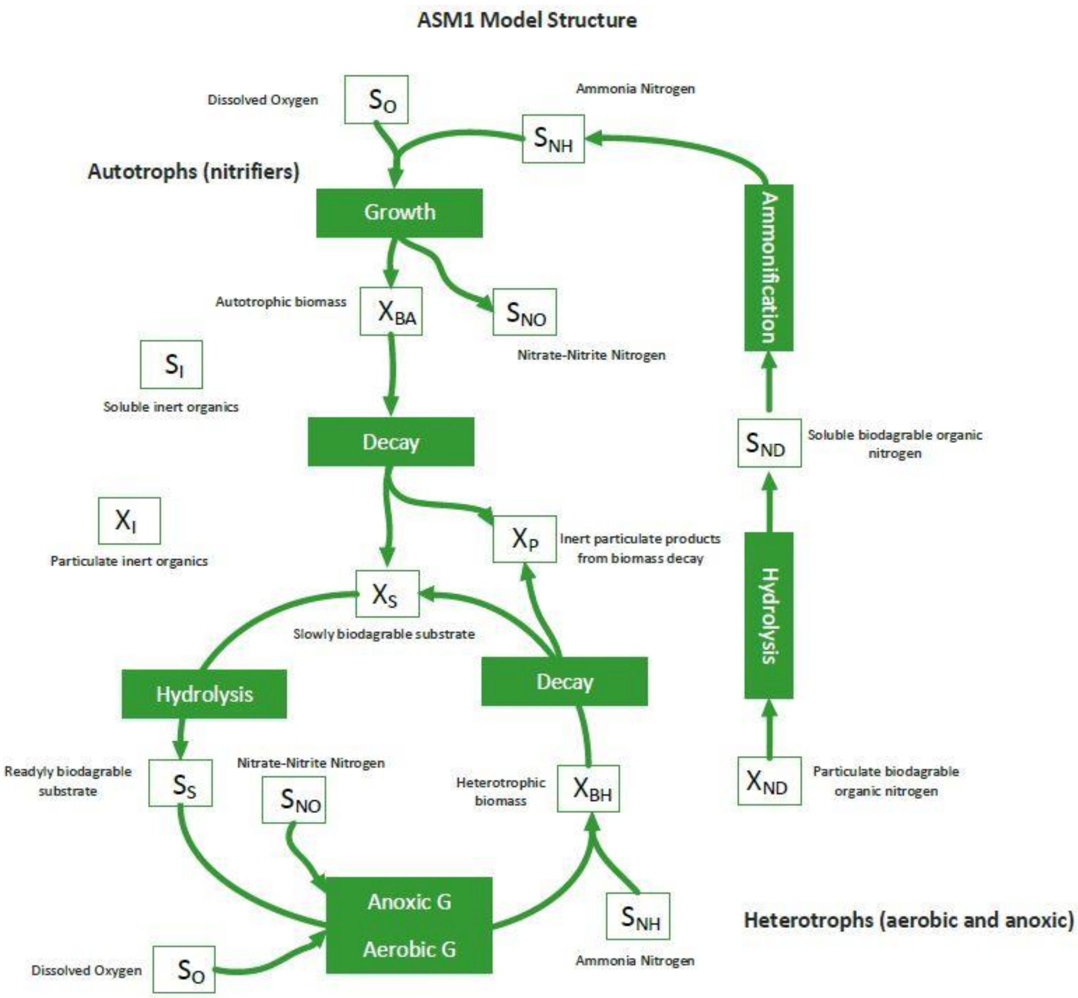

Figure 4.5 ASM1 model structure

By this research, the sub-systems of a plant are modeled as simple as possible to obtain fast solutions on a well-established, efficient and elastically adaptable plant simulator. The distinctly performed simulations for each component (block - process) of a plant are available to check the utility of any proposed treatment system [90]. The biological treatment involves carbonaceous and nitrogenous components. These components are presented in Figure 4.6 and 4.7 [52].

4.3.1 Carbonaceous Components

In the ASM, the zones for carbon degradation and anoxic zones and nitrification are distinguished strictly. The assumption for aerobic zones due to aeration system is that supply of dissolved oxygen is sufficient for aerobic zones due to aeration installations. In the corresponding process equations non-linear monod-terms are replaced by constant factors that can be used for calibration. It is difficult to establish model parameters since certain parameters are not measurable in realistic operation. [101].

Recent IWA models comprising ASM1, ASM2 and ASM3 have proven to be outstanding instruments for modeling processes of carbon oxidation, nitrification, denitrification and biological phosphorus removal. [121].

However, the effect of long-term environmental factors such as temperature on the removal of organic carbon and nitrogen has so far received relatively little attention [14] and thus a full-scale WWTP should be elaborated in more detail. Temperature and other disturbances for the processes of nitrification, endogenous degradation, hydrolysis and ammonification are taken into account. [49][122].

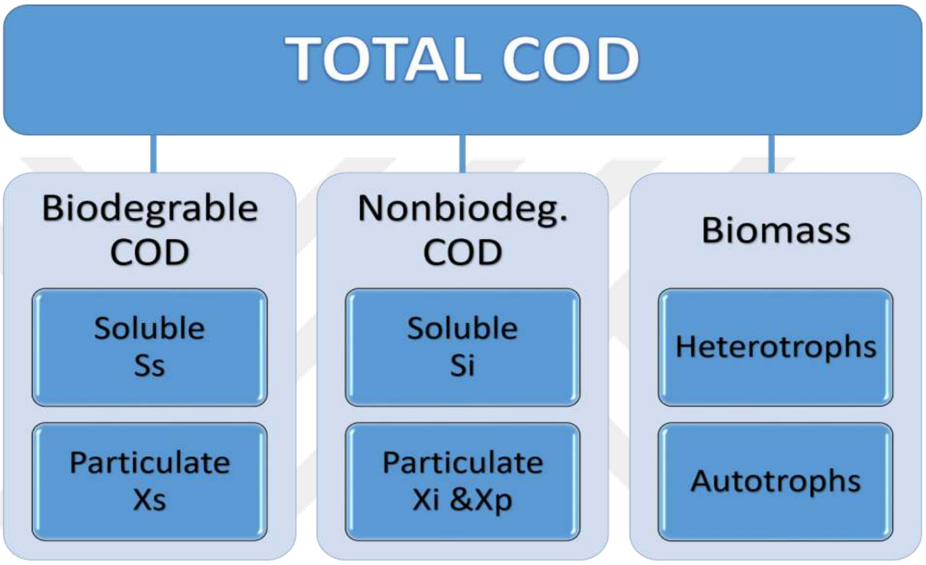

Figure 4.6 Carbonaceous components

4.3.2 Nitrogenous Components

In WWTPs, biological processes of nitrification and denitrification shown in Figure 4.7 are used for removing nitrogen compounds. The efficiency parameters determined via biological processes of nitrogen removal are starting from BOD5 to Total Kjeldahl Nitrogen (TKN), temperature and pH.

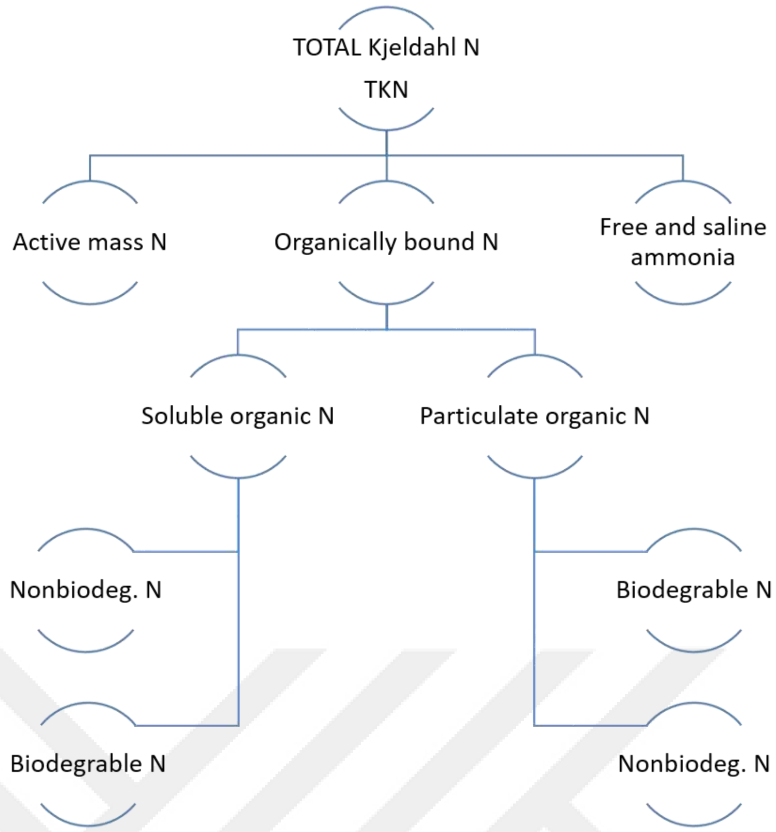

Figure 4.7 Nitrogenous components

For the aerobic growth of heterotrophs; compared to traditional sludge flocs, aerobic granules have more compact structure, better settling capacity and greater biomass retention. Studies show that it is possible to use aerobic granules to treat high-strength waste water, at the same time extract organic matter, nitrogen and phosphorus [123]. Both the substrate (S_S) and soluble oxygen (S_O) may effect the growth process and removal of COD change Both the substrate (S_S) and oxygen (S_O) may affect the growth process and the change in COD [124].

Process rate of aerobic growth of heterotrophs is defined as:

$$\hat{\mu}_H \left(\frac{S_S}{K_s + S_S}\right)\left(\frac{S_O}{K_{O,H} + S_O}\right) X_{B,H} \tag{4.25}$$

For anoxic growth of heterotrophs; Anaerobic (Anoxic) treatment of wastewater is conducted in an atmosphere without molecular oxygen by anaerobic microorganisms processing organic and inorganic substances. During this biological cycle, micro-organisms known as acid builders transform organic compounds into organic acids. Methane-forming organisms then convert the organic acids to methane and CO_2 gases [125].

Process rate of anoxic growth of heterotrophs is equal to:

$$\hat{\mu}_H\left(\frac{S_S}{K_s+S_S}\right)\left(\frac{K_{O,H}}{K_{O,H}+S_O}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\eta_g X_{B,H} \tag{4.26}$$

For aerobic growth of autotrophs; recently, the aerobic digestion of activated sludge has been utilized in some WWTPs as an alternative to the more traditional anaerobic digestion. There are many advantages associated with aerobic digestion such as high efficiency (i.e. a complete depletion of solids, no pungent gases, rapid biodegradability, wide ranging with many applications , a lower capital investment and fewer operational problems [55]. In addition, aerobic digestion has impact resistance and strong adaptability. For instance, a short detention time of about 15 days at a temperature of 20 degrees centigrade is usually sufficient to produce sludge that can be easily dewatered, whereas anaerobic digestion needs a detention time of 22 days at a temperature of 15 to 45 degrees centigrade [126]–[128].

For aerobic growth of autotrophs process rate is:

$$\hat{\mu}_{\mathbf{A}}\left(\frac{S_{\mathbf{NH}}}{K_{\mathbf{NH}}+S_{\mathbf{NH}}}\right)\left(\frac{S_O}{K_{O,\mathbf{A}}+S_O}\right)X_{B,\mathbf{A}} \tag{4.27}$$

For the decay of heterotrophs; in ASM1, the standard activated sludge WWT processes (e.g. hydrolysis, growth and degradation of organisms, etc.) have been developed as the most frequently used models [129].

For the decay of heterotrophs the process rate condition below:

$$b_H X_{B,H} \tag{4.28}$$

The decay rate of the autotrophs for nitrogen and phosphorus. The combination physical-chemical method is reliable [130] and modeled in same way as decay of heterotrophs.

Similar to heterotrophs process rate, the decay rate of the autotrophs is defined as:

$$b_A X_{B,A} \tag{4.29}$$

For ammonification of soluble organic nitrogen, as defined in ASM1, the influential total nitrogen TKN consists of NH4-N ($S_{\mathbf{NH}}$) ammonia nitrogen, soluble organic nitrogen (S_{ND}) and particulate nitrogen ($X_{\mathbf{ND}}$).

It is possible to formulate the transformations between influential nitrogen components as follows. S_O, appropriate calculations for the determination of nitrogen fractions can be made using the average monthly nitrogen data given in Figure 2.11 (The process kinetics was adopted from original ASM1 model [122]) [128].

Ammonification of soluble organic nitrogen process rate:

$$k_a S_{ND} X_{B,H} \tag{4.30}$$

There are three biochemical processes (hydrolysis of entrapped organics, aerobic growth of heterotrophs and aerobic decay of heterotrophs) that are described in ASM1 concept [124]. Hydrolysis of entrapped organics is considered in (Figure 4.5)

For the hydrolysis of entrapped organic nitrogen defined process rate in ASM is below:

$$k_h \left(\frac{\frac{X_s}{X_{B,H}}}{K_x + \left(\frac{X_s}{X_{B,H}}\right)} \right) \left\{ \left(\frac{S_O}{K_{O,A} + S_O} \right) + \eta_h \left(\frac{K_{O,H}}{K_{O,H} + S_O} \right) \left(\frac{S_{NO}}{K_{NO} + S_{NO}} \right) \right\} X_{B,H} \tag{4.31}$$

Another was that as the amount of trapped substrate became high in proportion to the biomass, the rate tended to saturate. Finally, by analogy with the use of readily biodegradable substrate, it was reasoned that the rate would depend on the present electron acceptor concentration.

Since under anaerobic conditions little was known about "hydrolysis" except for the minimal decay knowledge provided earlier, it was agreed to conclude that in the absence of both oxygen and nitrate, the rate goes to zero. Obviously, on this topic, further experimental work is needed.

Organic nitrogen was expected to be distributed evenly across the slowly biodegradable substrate, so that the rate of hydrolysis of trapped organic nitrogen was actually taken to be equal to the rate of hydrolysis of the slowly biodegradable substrate. [128]. Biodegradable organic particulate nitrogen is broken down to soluble organic nitrogen at a rate specified by the hydrolysis reaction shown in Figure 4.5 for trapped organics.

Process rate of hydrolysis of entrapped organic nitrogen is defined as:

$$\rho_7 \frac{X_{ND}}{X_S} \tag{4.32}$$

where

$$\rho_7 = k_h \left(\frac{\frac{X_s}{X_{B,H}}}{K_x + \left(\frac{X_s}{X_{B,H}}\right)} \right) \left\{ \left(\frac{S_O}{K_{O,\mathbf{A}} + S_O} \right) + \eta_h \left(\frac{K_{O,H}}{K_{O,\mathbf{H}} + S_O} \right) \left(\frac{S_{NO}}{K_{NO} + S_{NO}} \right) \right\} X_{B,\mathbf{H}} \tag{4.33}$$

4.4 Sedimentation Tank and Aeration System Models

4.4.1 Sedimentation Tank Model

The finite element methods are widely used to solve governing equations of sedimentation by dividing the sedimentation tank to several layers as shown in Figure 10 [49]. The dispersion and compressions have been considered by Bürger-Diehl sedimentation model [131], [132]. The Godunov flux model focuses on the concentrations of layers between layer j and layer $j + 1$ [133].

$$G_j = G_j(C_j, C_{j+1}) := \begin{cases} \min\limits_{C_j \le C \le C_{j+1}} f_{bk}(C) & \text{if } C_j \le C_{j+1} \\ \max\limits_{C_{j+1} \le C \le C_j} f_{bk}(C) & \text{if } C_j > C_{j+1} \end{cases} \tag{4.34}$$

The method can evaluate the unknowns, if the Vesilind velocity function is used because f_{bk} has precisely one local maximum at $\hat{C}$. These layers can be used to calculate the effluent and underflow concentrations [134]. Therefore, sedimentation is not realized for the underflow layer. The effluent and underflow concentrations are shown in Figure 4.10.

The concentration is modelled by Burger model as the following:

$$\sigma_e(C) = \begin{cases} 0 & \text{for } C < C_c \\ \alpha \ln\left(1 + \frac{C - C_c}{\beta}\right) & \text{for } C \ge C_c \end{cases} \tag{4.35}$$

This model is improved with the stress function proposed by De Clercq [135].

$$d_{comp}(C)=\begin{cases} 0 & \text{for } 0\leq C<C_c \\ \dfrac{\rho_s \alpha v_0 e^{-r_v C}}{g(\rho_s-\rho_f)(\beta+C-C_c)} & \text{for } C\geq C_c \end{cases} \tag{4.36}$$

The effective depth of the sedimentation tank is shown in Figure 4.8. For defining the effective depth, WOA is used. The objective space is shown in Figure 4.9.

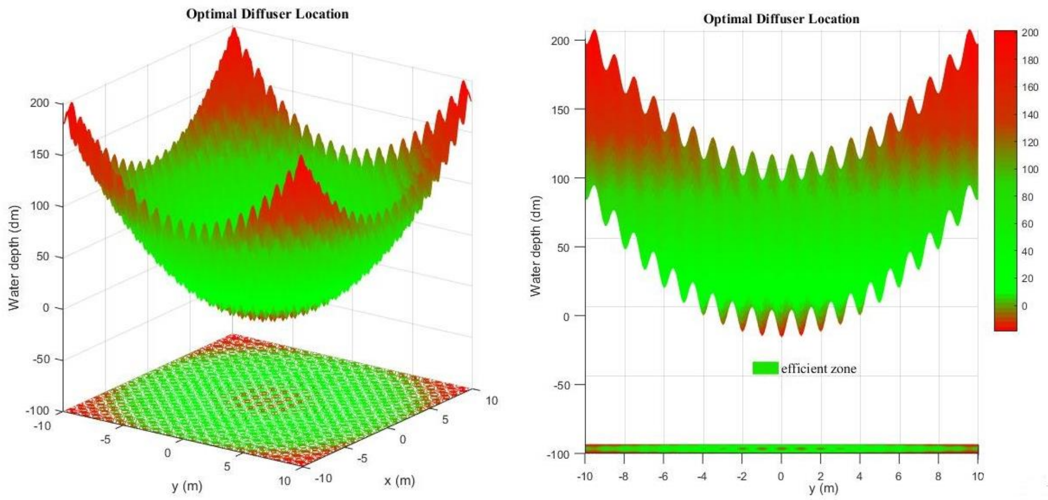

Figure 4.8 Optimal location of diffusers in three dimensional view (left), in side view (right)

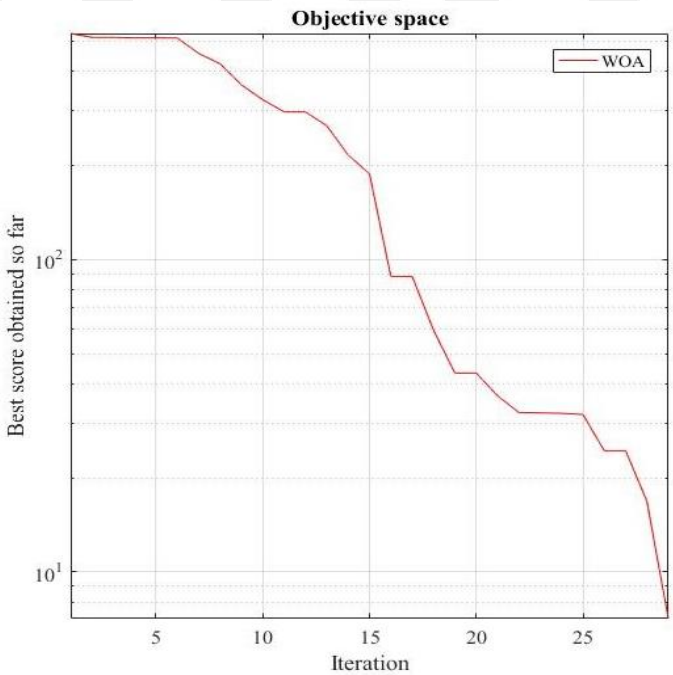

Figure 4.9 WOA objective space

The model proposed by Kynch [136] describes the nonlinear behavior of the sludge concentration at $C(z,t)$, at depth z from the feed level and at time t as,

$$\frac{\partial C}{\partial t} = -\frac{\partial}{\partial z}F(C,z,t)\frac{\partial}{\partial z}\left(\left\{\gamma(z)d_{comp}(C) + d_{disp}(z, Q_f(t))\right\}\frac{\partial C}{\partial z}\right) + \frac{Q_f(t)C_f(t)}{A}\delta(z) \tag{4.37}$$

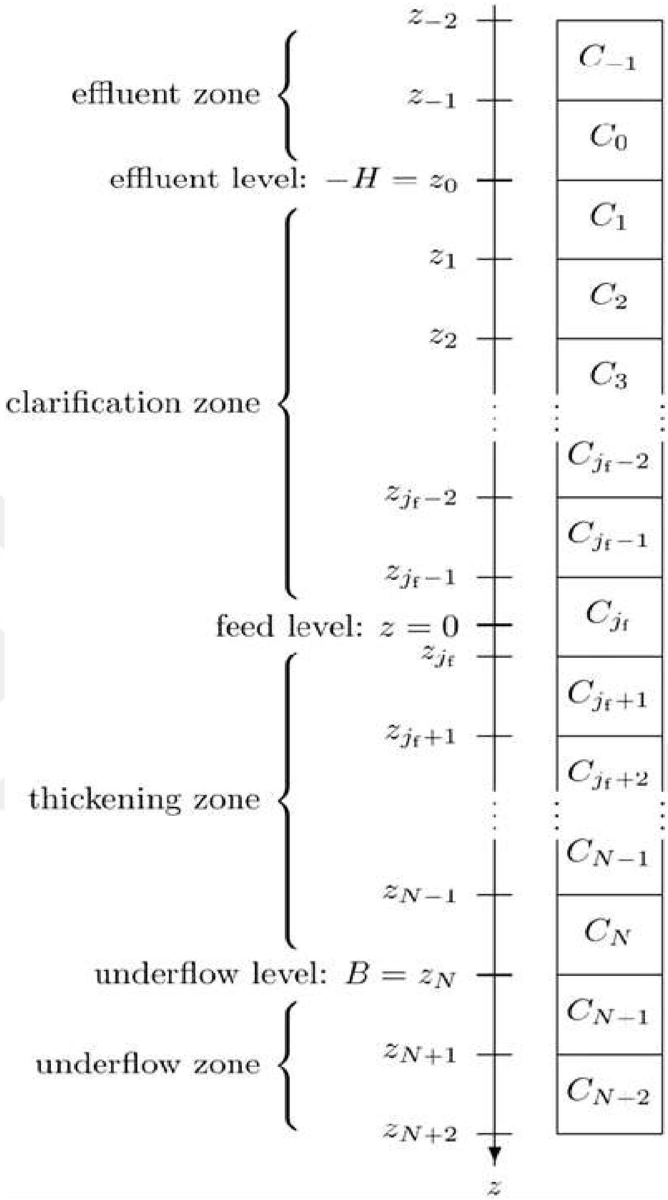

Figure 4.10 Layer discretization [134]

$F(C,z,t)$ is the convective flux function which represents the hindered settling flux with bulk flows. This can be determined by Godunov's flux for numerical approximation, in which $d_{comp}(C)$ and $d_{disp}(z, Q_f(t))$ are the compression and dispersion terms.

$$d_{disp}(z, Q_f) = \begin{cases} \alpha_1 Q_f \exp\left(\frac{z^2/(\alpha_2 Q_f)^2}{1-|z|/(\alpha_2 Q_f)}\right) & \text{for} |z| < \alpha_2 Q_f \\ 0 & \text{for } |z| > \alpha_2 Q_f \end{cases} \tag{4.38}$$

It is assumed that d_{disp}, the dispersion coefficient, is a dependent function on two factors, the volumetric feed flow and inlet region where mixing occurs. The Return Activated Sludge (RAS) and velocity of the sedimentation in 30 minutes is obtained by [137]–[139]

$$SSV_{30} = \frac{\text{VoSS in 30 minutes, ml}}{\text{Sample Volume, ml}} \times \frac{100\text{ ml}}{\text{litre}} \tag{4.39}$$

$$SVI = \frac{SSV_{30}\text{ (ml/lt)}}{\text{MLSS (ml/lt)}} \times \frac{1000\text{ mg}}{\text{g}} \tag{4.40}$$

$$r = \frac{Q_r}{Q} = \left[\frac{100}{\text{MLSS}(\%) \times \text{SVI(ml/g)}} - 1\right]^{-1} \tag{4.41}$$

$$r = \frac{Q_r}{Q} = \left[\frac{\text{MLSS(mg/l)}}{\frac{10^6}{\text{SVI}} - \text{MLSS(mg/l)}}\right] \tag{4.42}$$

4.4.2 Aeration System

The greatest energy consumption takes place in the aeration systems internally, which changes between 53% and 68% of a WWT plant, depending on the process [140].

Modified analytic expression of the dissolved salts in wastewater including the composition and concentration can be defined as:

$$C_s = C_0.\exp\sum_{i=0}^{n}(K_{iCi})^{-1} \tag{4.43}$$

Taking into account the nonlinear dependence of water density on temperature [14]:

$$p_h = d.g.h = (-0.006\Theta^2 + 0.0365\Theta + 999.91).g.h \tag{4.44}$$

$$C_S = C\left(r_{O_2}, p_a, \Theta, K, c_i, h\right) = \frac{0.668 r_{O_2}.\left(p_a + (-0.006\Theta^2 + 0.0365\Theta + 999.91).g.h.10^{-3}\right)}{\exp(\sum K_i c_i + 0.0219\Theta)} \quad (4.45)$$

The dynamic model of dissolved oxygen in the conventional aeration tank is described by the nonlinear differential equation below [141]:

$$\frac{\Delta So(t)}{\Delta t} = k_{La}\left(Q_{air}(t)\right)\left(So_{sat} - So(t)\right) - \frac{So(t)}{K_o + So(t)} \times R_r(t) \quad (4.46)$$

where $So_{sat} = 8.637\ gO_2/m^3$ denotes dissolved oxygen saturation concentration, and $K_o = 0.2\ g/m^3$ is the Monod's constant. $k_{La}\left(Q_{air}\right)$ function describes the oxygen transfer and depends on the aeration system and sludge conditions. This function is presented with different model approaches[18] including the linear model [33]:

$$k_{La}(Q_{air}) = \alpha.\, Q_{air}(t) \quad (4.47)$$

where $\alpha = 0.208\ 1/m^3$. The performance function J is defined as

$$J = \sum_{i=1}^{H_p} \left\{So\left(k + \frac{i}{k}\right) S^{ref}\left(k + \frac{i}{k}\right)\right\}^2 + \sum_{i=1}^{H_p} P_c\left(k + \frac{i}{k}\right) \quad (4.48)$$

where the first term on the right hand side of (4.47) is the tracking error, and the second term defines the control cost on a prediction horizon H_p. The equivalent weights in the control cost are used to achieve a desired compromise between the tracking error, the intensity of switching the blowers, and the cost of the energy used for pumping air [142]. The studies on the electrical analogy which pay effort to represent the system in electrical terms as presented by Piotrowski and Krawczyk [7] can be used to create an electrical network for modeling the aeration system [15], [142], [143], the result of which is depicted in Figure 4.11.

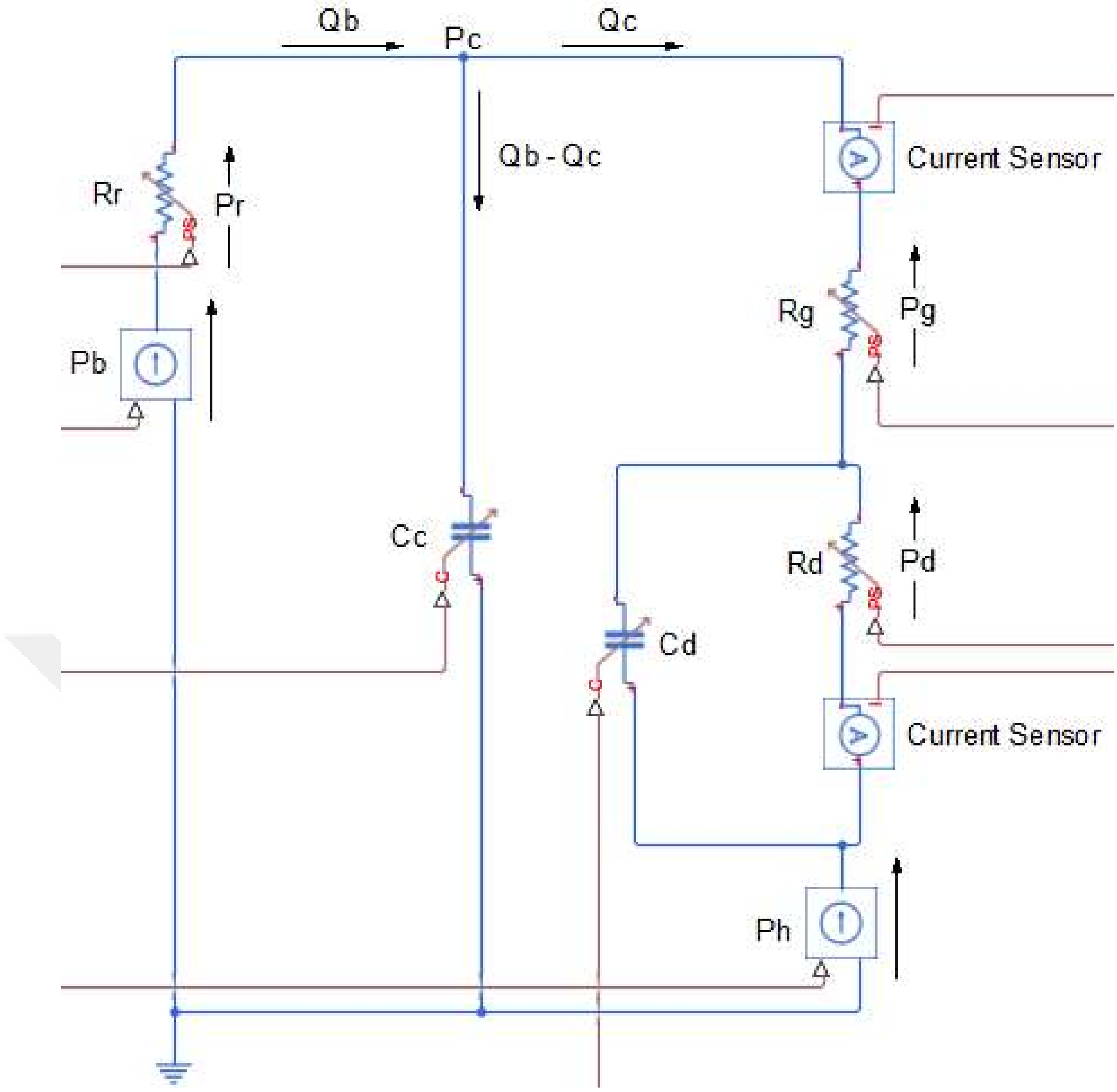

Figure 4.11 Electrical analogy of the aeration system model simulation setup [143]

4.7 UTM Concept

In order to simplify the complex and detailed process of WWT, the diagram of a typical WWTP is shown in Figure 2.6. The process of secondary treatment is the main focus of the current research, which includes the aeration process as shown in the figure.

In this study, a UTM for the aeration and sedimentation processes is proposed. The aim is to unify the tanks used for two processes distinctly in a single tank, which has a similar structure to a conventional sedimentation tank. The algorithm for the conventional SBR follows several steps that are performed in a tank respectively as shown in Fig 4.12. This sequence is continuously conserved in UTM.

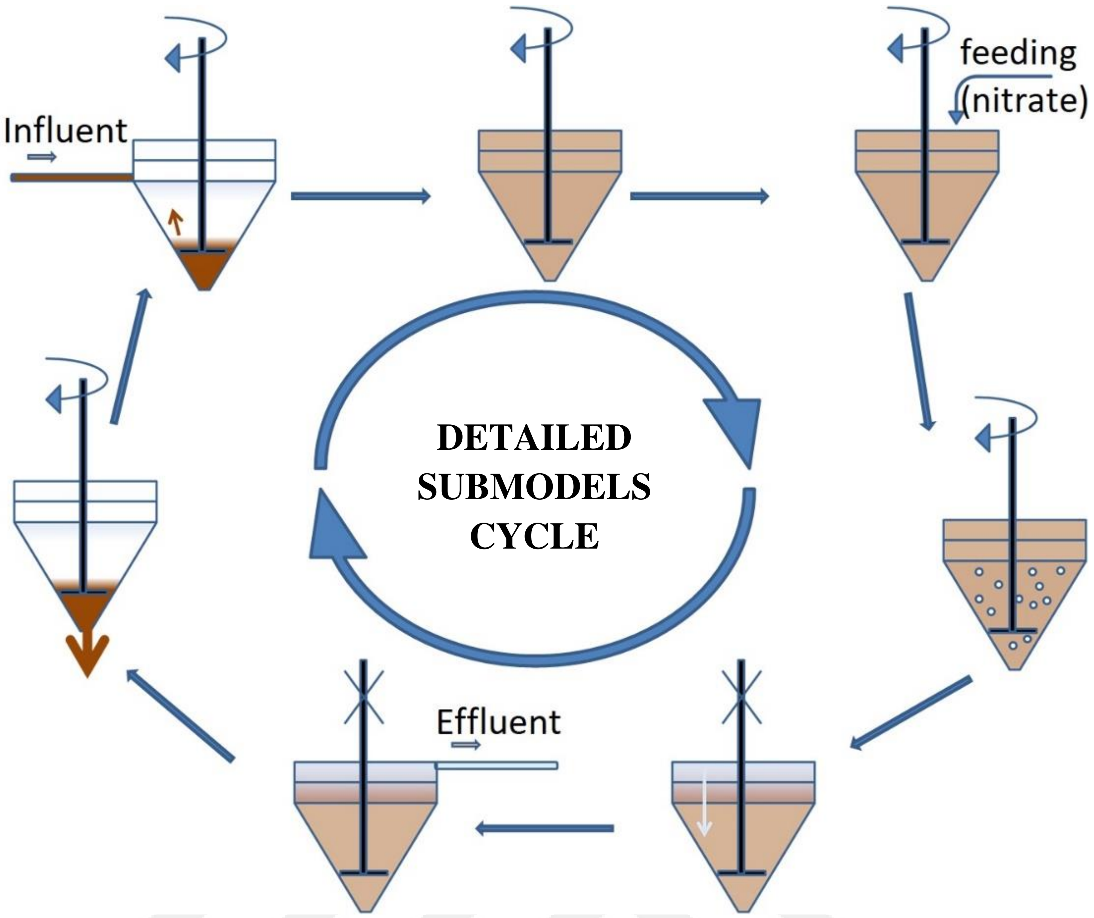

Figure 4.12 Sequencing batch reactor operation system adapted to UTM

The conventional system consists of two interconnected water tanks, two submersible pumps and blower pumps. Since the amount of RAS remains constant in UTM, the effect of pumps used for sludge return can be neglected in the model. Influent water characteristics are the inputs while the treated water overflow from the conic tank and waste sludge produced after the process are the outputs. Treated water is discharged via several level taps. Discharging cycle starts after sufficient amount of sedimentation is obtained. The system structure of the UTM is shown in Figure 4.13.

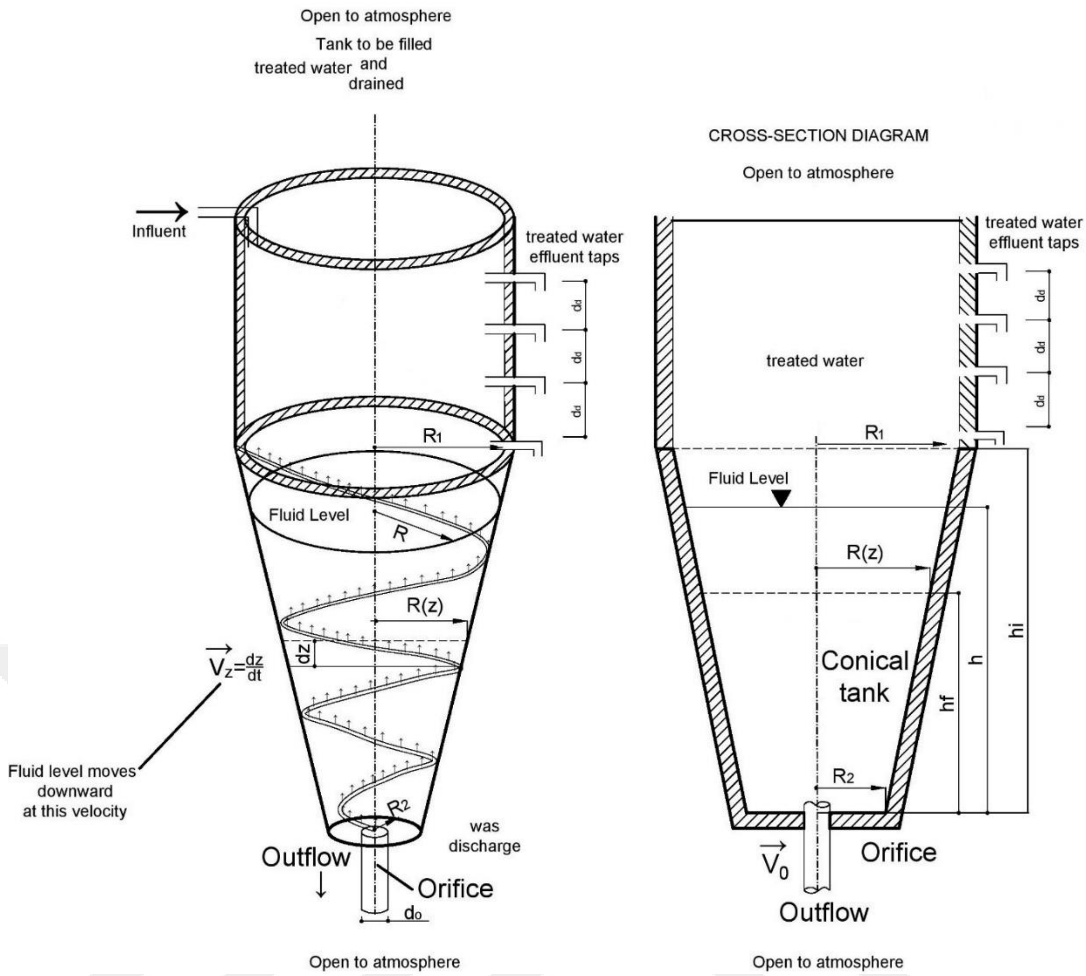

Figure 4.13 Unified tank model

The Unified Tank Model, unlike the conventional systems, involves a conical tank configuration used for both aeration and sedimentation processes. Along with the physical charging and discharging; aerobic, anaerobic and sedimentation phases are alternatively modeled in UTM, which is used for modeling the activated sludge process in a unified tank that includes both biological reactions and solid–liquid separation periodically. Beside the advantages of SBR such as flexibility of operation, low cost and small footprint technology [144], the UTM offers a sequence of successive phases that can be adapted to the existing plants with low-cost modifications. This provides the required combination for the growth conditions in removing contaminants with different types of microorganisms from wastewater.

In this study, an optimized aeration system model in the form of UTM is proposed that helps to obtain a more homogeneous and efficient aeration solution based on DO optimization for the UTM obtained via WOA. The mathematical model of the conventional structure with two separate tanks is presented. The UTM mathematical model is derived according to the existing studies on conventional WWTPs. The dynamic model is adapted to the UTM and numerical simulations are presented. The functional specifications and the objectives of the process (purpose, accuracy, boundaries, time scale, etc.) have been clarified. For physical charging and discharging durations of the unified tank volume, some deterministic models have been used including finite element approaches for settling process. The aeration system has been modelled with electrical analogy to obtain a more realistic model. For biological processes, the experimental researches and models have also been presented [37].

4.7.1 Mathematical Model of Unified Tank Volume

The tank models and mass conservation principle for different shapes are introduced and clearly summarized by Yetilmezsoy [145]. The total mass in a controlled volume (CV) in a period of Δt is;

Total mass of influent − Total mass effluent = Net change of mass

$$\sum m_{in}^{*} - \sum m_{out}^{*} = \frac{dm_{CV}}{dt} = \frac{dm_{eff} - dm_{inf}}{dt} \tag{4.49}$$

As velocity coefficient (C_V) depends on energy losses between charging and discharging points and the contraction coefficient (C_c); discharge coefficient (C_d) is calculated as [146];

$$C_d = C_v C_c \tag{4.50}$$

The flow rate output from the Calculated Volume (CV) can be described as;

$$Q_{out} = (C_V v_o)(C_c A_0) = [C_v \sqrt{2gz}]\left[C_c\left(\pi \frac{d_0^2}{4}\right)\right] = C_d \sqrt{2gz}(\pi \frac{d_0^2}{4}) \tag{4.51}$$

$$-(Q_{out}) = \frac{d(V_{CV})}{dt} \rightarrow -\left[C_d \sqrt{2gz}\left(\pi \frac{d_0^2}{4}\right)\right] \tag{4.52}$$

$$= \frac{Q_{CV} dt}{dt} = \frac{[vA(z)]dt}{dt} \tag{4.53}$$

$$-[C_d \sqrt{2gz}\left(\pi \frac{d_0^2}{4}\right)] = \frac{[vA(z)]dt}{dt} \tag{4.54}$$

$$= \frac{\left[\left(\frac{dz}{dt}\right) A(z)\right] dt}{dt} = \frac{dzA(z)}{dt} \tag{4.55}$$

$$-\left(\frac{dz}{dt}\right) A(z) = [C_d \sqrt{2gz} (\pi\, d_0^2/4)] \rightarrow \int_0^T dt \tag{4.56}$$

$$= -\int_{h_i}^{h_f} \frac{A(z)dz}{C_d \sqrt{2gz} (\pi\, d_0^2/4)} \tag{4.57}$$

where the mathematical model of conic tank shown in Figure 4.13. is modeled in the following [145]. Cross-sectional area of the UTM depends on the wastewater height z and the radius R(z) of the UTM. Therefore the cross-sectional area A(z) of the UTM is defined as a function of z (m^2) as follows:

$$A(z) = \pi . \left[\left(\frac{{R_1}^2 + {R_2}^2 - 2R_1R_2}{{h_i}^2}\right) z^2 + \left(\frac{2R_1R_2 - 2{R_2}^2}{h_i}\right) z + \left({R_2}^2\right)\right] \tag{4.58}$$

$$A(z) = \pi[(\beta_2)z^2 + (\beta_1)z + (\beta_0)] \tag{4.59}$$

Substituting (4.56) into (4.58),

$$\int_0^T dt = -\int_{h_i}^{h_f} \frac{[\pi(\beta_2)z^2 + (\beta_1)z + (\beta_0)]dz}{C_d \sqrt{2gz} (\pi {d_0}^2/4)} \tag{4.60}$$

$$= \frac{\pi}{C_d \sqrt{2g} (\pi {d_0}^2/4)} \tag{4.61}$$

Using (4.58-4.61), the discharge time T (calculated discharge time (s)) for the UTM is obtained from the equations below:

$$\int_0^T dt = -C_d \int_{h_i}^{h_f} \frac{\beta_2 z^2 + \beta_1 z + \beta_0}{\sqrt{z}} dz \tag{4.62}$$

$$= C_d \int_{h_f}^{h_i} (\beta_2 z^{3/2} + \beta_1 z^{1/2} + \beta_0 z^{-1/2}) dz \tag{4.63}$$

$$T = C_d\left[\left(\beta_2\frac{2}{5}h_i^{\frac{5}{2}} + \beta_1\frac{2}{3}h_i^{\frac{3}{2}} + \beta_0 2h_i^{\frac{1}{2}}\right) - \left(\beta_2\frac{2}{5}{h_f}^{5/2} + \beta_1\frac{2}{3}{h_f}^{3/2} + \beta_0 2{h_f}^{1/2}\right)\right] \tag{4.64}$$

$$T = \left(\frac{\pi}{C_d\sqrt{2g}\left(\pi {d_0}^2/4\right)}\right)\left|(\lambda_1) - (\lambda_2)\right| \tag{4.65}$$

The discharge coefficient (C_d) for the UTM is obtained from (4.64) with respect to $|(\lambda_1) - (\lambda_2)|$ and T_{exp} (experimental discharge time (s)) as:

$$C_d = \frac{T_{exp}}{(\lambda_1 - \lambda_2)} = \frac{\pi}{C_d\sqrt{2g}\left(\pi.\,{d_0}^2/4\right)} \tag{4.66}$$

$$= \frac{2\sqrt{2}(\lambda_1 - \lambda_2)}{T_{exp}}\left(\frac{1}{d_0}\right)^2\left(\frac{1}{g}\right)^{0.5} \tag{4.67}$$

The wall steep angle is another design parameter that affects aeration and oxygen solubility. The wall steep angle (Wa) is calculated based on basic geometric calculations as;

$$Wa = \tan^{-1}\left(\frac{hi}{(R_1 - R_2)}\right) \tag{4.68}$$

To reach an empirical benchmark between the classical oxidation and the UTM aeration system depicted in Figure 4.14, it is assumed that the liquid density, volume in tanks and the number of diffusers are equal for both cases. The model is simulated with finite element methodology.

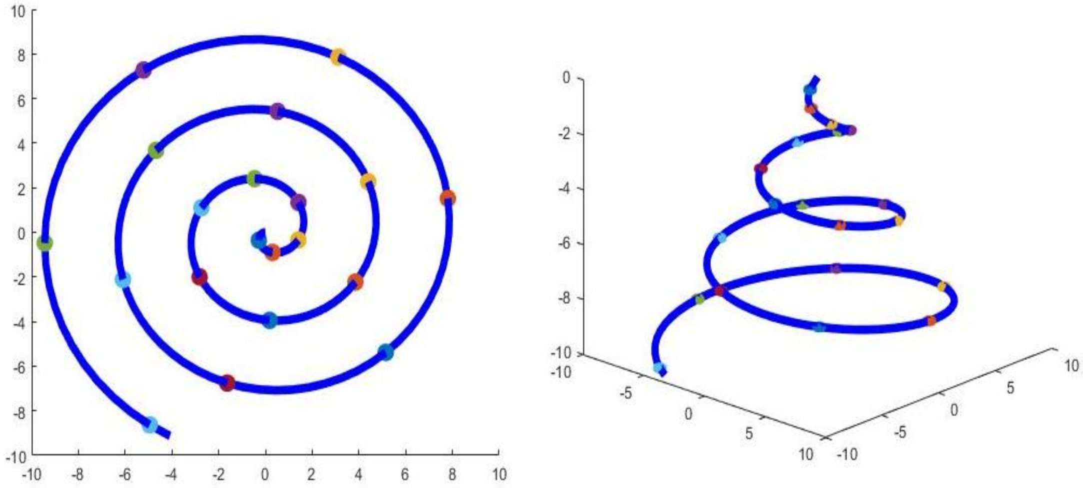

Figure 4.14 UTM aeration system in top view (left) and three dimensional view (right)

The WOA is applied to find optimal location of the diffusers in tank, which improves the aeration performance of the systems [147]. Constraints are effective diffuser radius (Dr), pressure tolerance of diffusers for efficient performance (Pn%), pool dimensions (L1, L2), water depth (Wd) and number of diffusers (Nd), as shown in Figure 4.14.

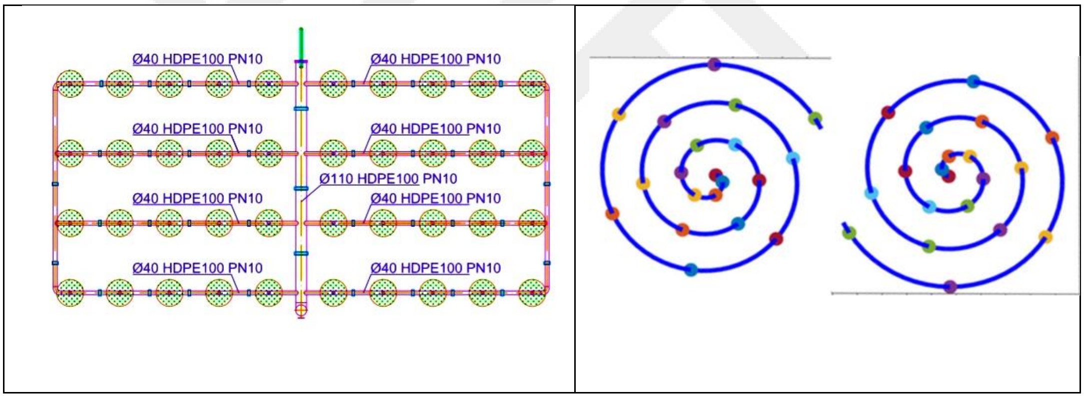

Figure 4.15 Conventional aeration (left) and proposed optimal solution (right)

As shown in Fig. 4.15, the location of diffusers in x-y plane are not homogeneously distributed. In limited pressure tolerance, a series of ghost diffusers are created and crossed with a genetic algorithm to obtain the nearest position of diffusers in x-y plane.

CHAPTER V

SIMULATOR DESIGN

5.1 Methodology

In addition to the forecast and long-short time planning facilities; operation, research and development, performance assessment steps are simulated in a user friendly simulator interface. The simulator proposes operational and constructive modifications. The outputs of the series of simulations are available to use in a new plant design.

The simulator proposes operational and constructive modifications. The outputs of the series of simulations are available to use in a new plant design. Design, construction and operational optimization solutions are obtained as follows,

- Design parameters are created for the use of similar characteristics WWTP.
- Constructive proposals are essential to define what type of constructive revisions are needed.
- Operational Solutions are useful to the configuration of equipment which in use.

The main system algorithm is shown in Figure 5.1

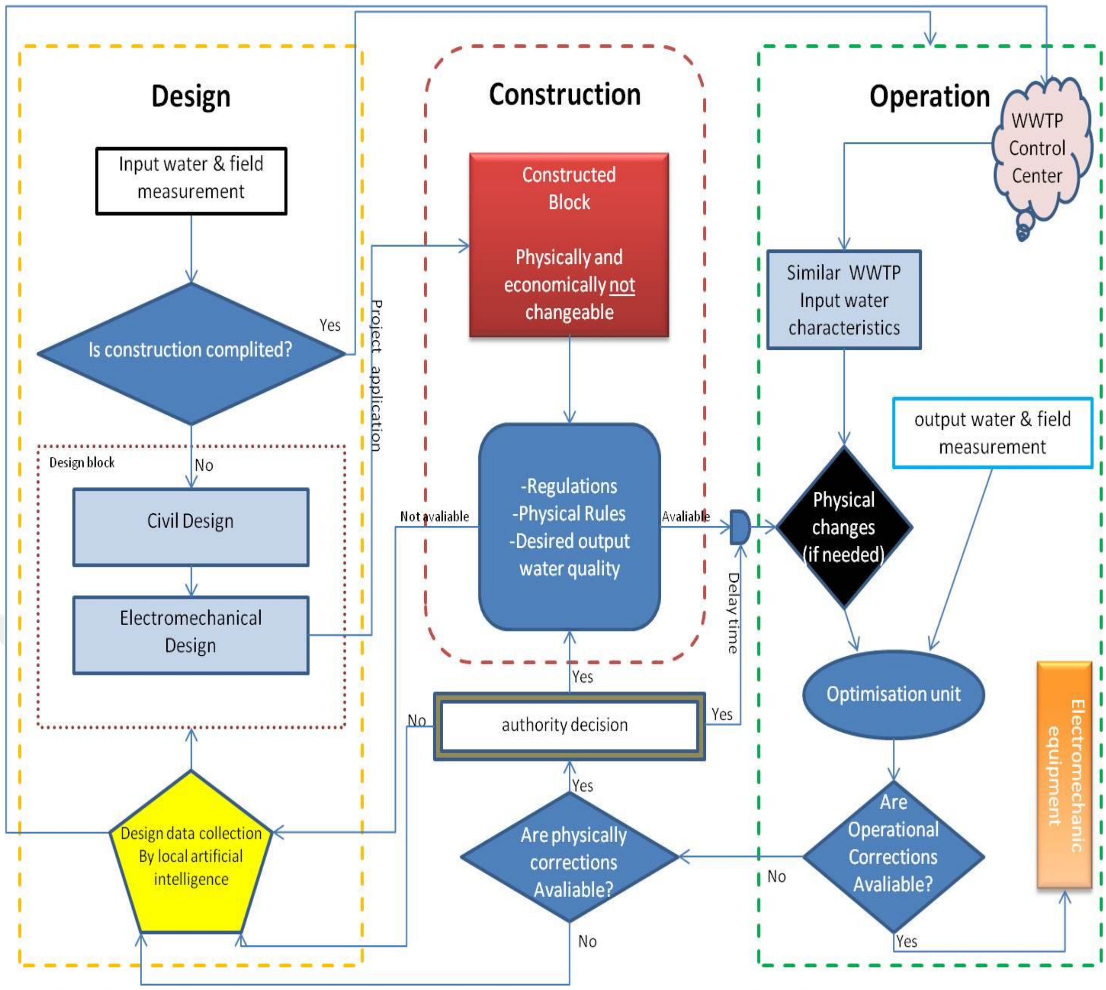

Figure 5.1 Main system algorithm

Based on literature review, the mathematical approach is guided to develop a Graphical Simulator for WWTP Design. Computer applications are available to solve the problem during the design procedure [92].

As a result, Graphical Simulator for WWTP including both environmental and efficiency concerns are solved by this study with several aspects [81]. The distinctly performed simulations for each component (block - process) of a plant are available to check the utility of any proposed treatment system [90].

5.2 Computer Application

Mathematical modelling is an important preliminary step for implementing the WWT processes guiding systems. Measurement accuracy as well as the testing of the control algorithms and check of the performances have to be evaluated for determination of the linearized structure of the model used in designing the control algorithm.

Mathematical modelling remains the most efficient research method, even though it sometimes leads to abstract models that only approximately describe the structure of these processes. The input-state output models developed in this study are the most widely used in the simulation technique and in biological process control, as they are directly compatible with the efficient simulation languages, amongst which computer environment holds the most significant position.

The excess of activated sludge wasted continuously from the secondary settler underflow at a constant rate is modelled. The schematizations of the elastic blocks of treatment plant simulator sub-models are presented in Figures 5.2-5.8.

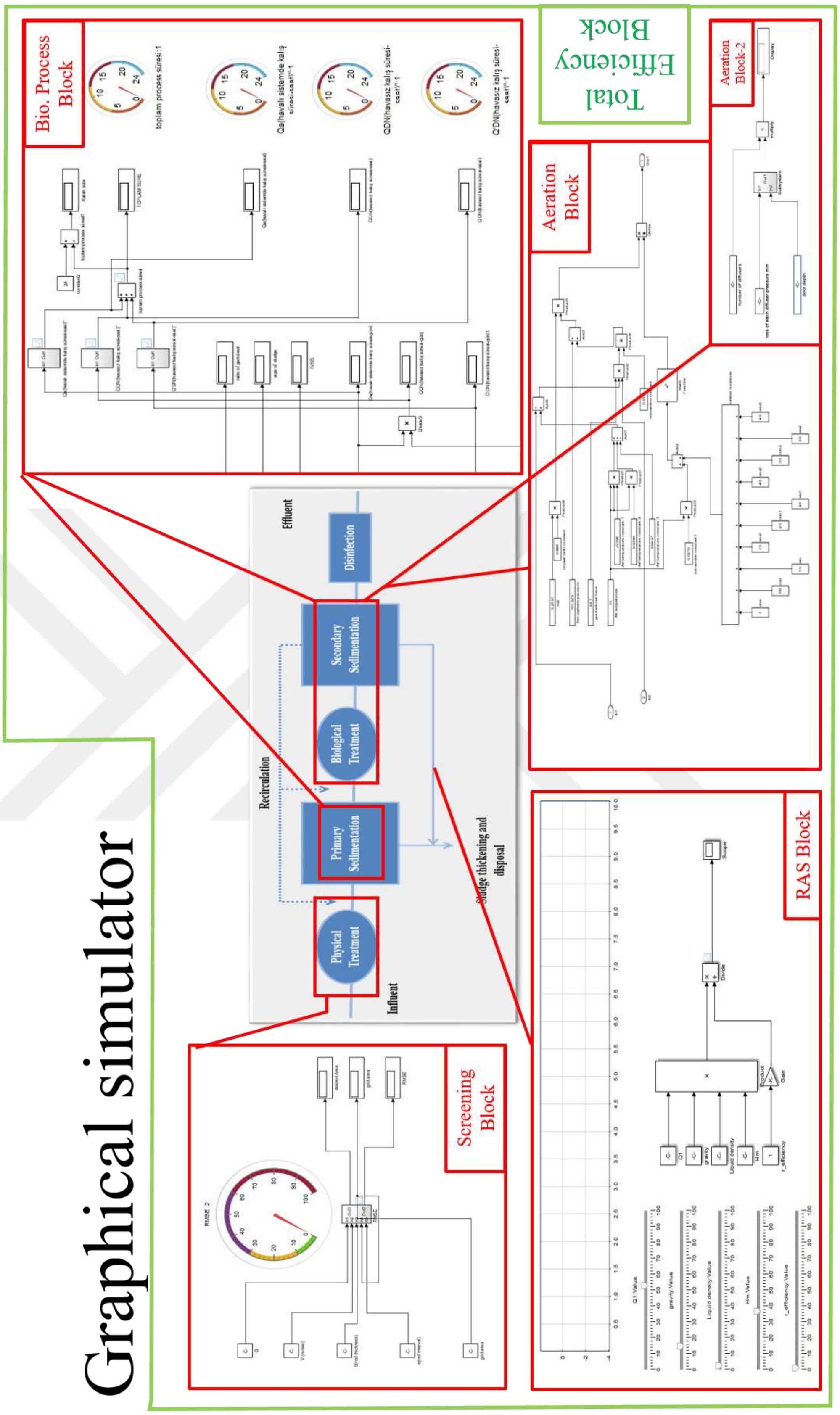

Figure 5.2 General Schematization of the WWTP graphical simulator

As a part of primary treatment; screening and grit chamber are simulated in the block shown in Figure 5.3. In order to avoid damage to the pumps and to avoid their accumulation in sludge digesters, grit chambers are basins to extract the inorganic particles. In literature, deterministic methods are commonly used for the design of grit chamber which take into account; settling velocity, surface overflow rate, detention period, bottom scour and flow through velocity, velocity of control devices, number of units, dimensions of each unit, loss of head [139].

In this study, a black box model is proposed for the grid chamber simulation by just measuring the flowrate and velocity. The flow rate and the velocity differences between the input and output gives an approximation for the water characteristics. The model block named as screening system is shown in Figure 5.3.

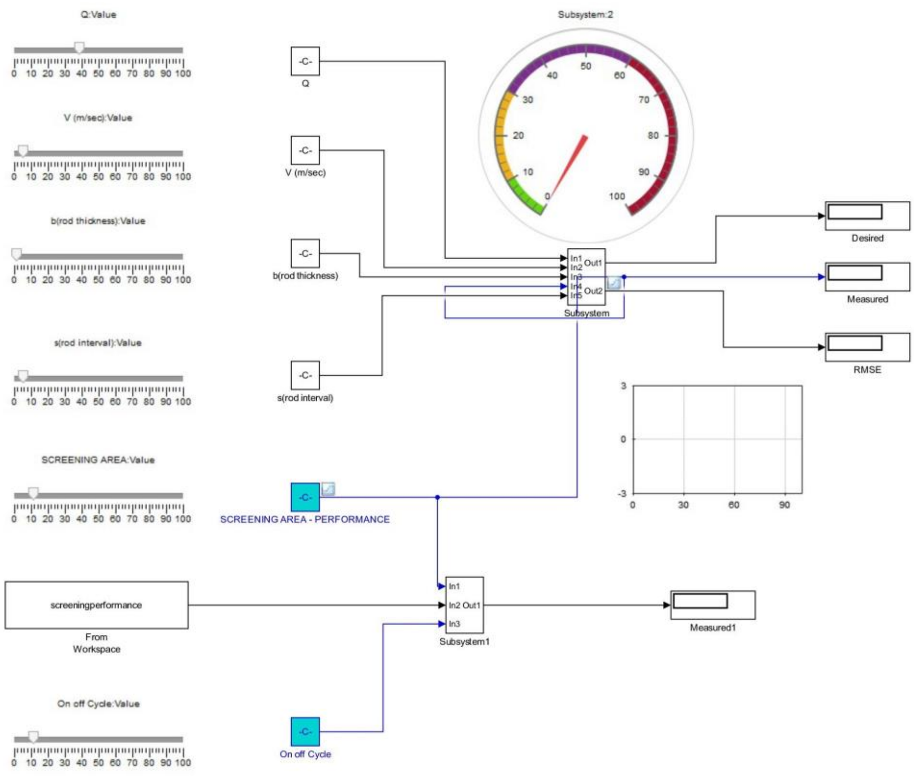

Figure 5.3 Schematization of the WWTP model of screening block

Physical durations of charging and discharging for both conical and rectangular shaped tank forms are simulated and presented Figure 5.4. The durations are essential parameters for the UTM concept as mentioned in previous sections. The cycle of the treatment and the capacity of the system are characterized by the comprehension of these parameters. The volume calculations and charging and discharging durations depending on the volume calculations for the conical tank are presented in section 4.7, UTM concept. The model of charging and discharging block shown in Figure 5.4 uses this mathematical background.

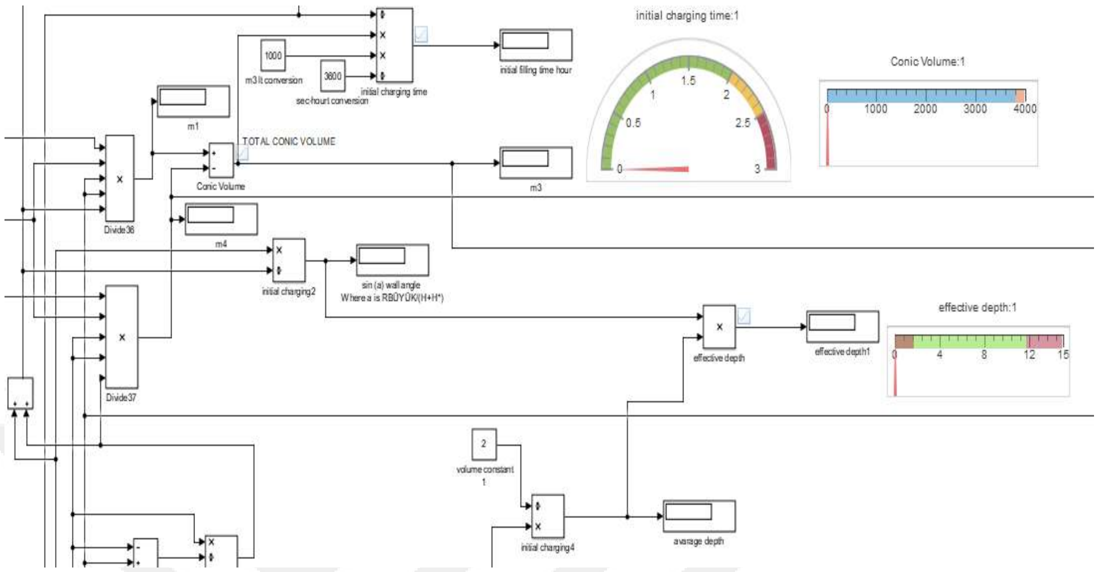

Figure 5.4 Schematization of the WWTP model charging and discharging block

Activated Sludge Model process rates has an important role in defining the RAS amount, aeration, anaerobic and aerobic durations. Simulations performed under the pump block, aeration blocks and retention time block are shown in Figure 5.5, Figure 5.6, Figure 5.7 and Figure 5.8 based on ASM.

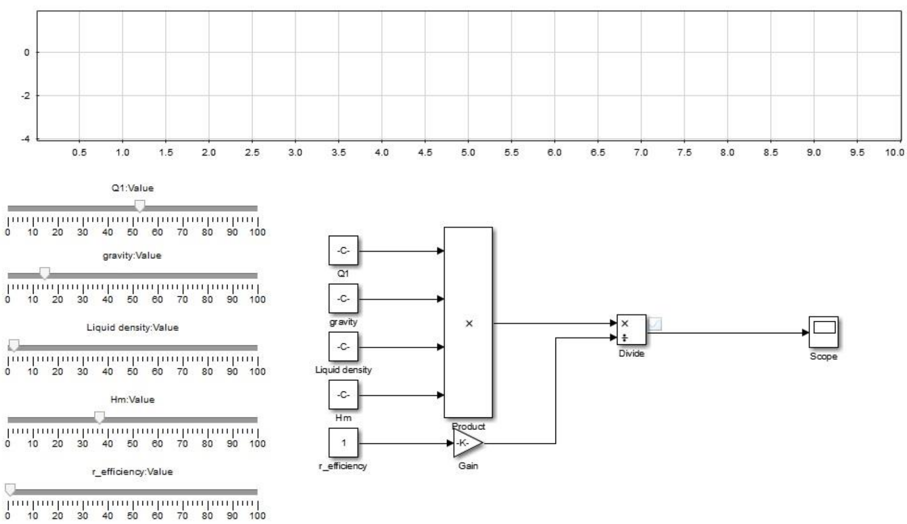

Figure 5.5 Schematization of the WWTP model pump block

Aeration system (RAS) is simulated in this block for both Conventional system (Aeration Block) and UTM Aeration Block-2 of a WWTP. Finite elements methods are used to define aeration system in UTM model Figure 5.6.

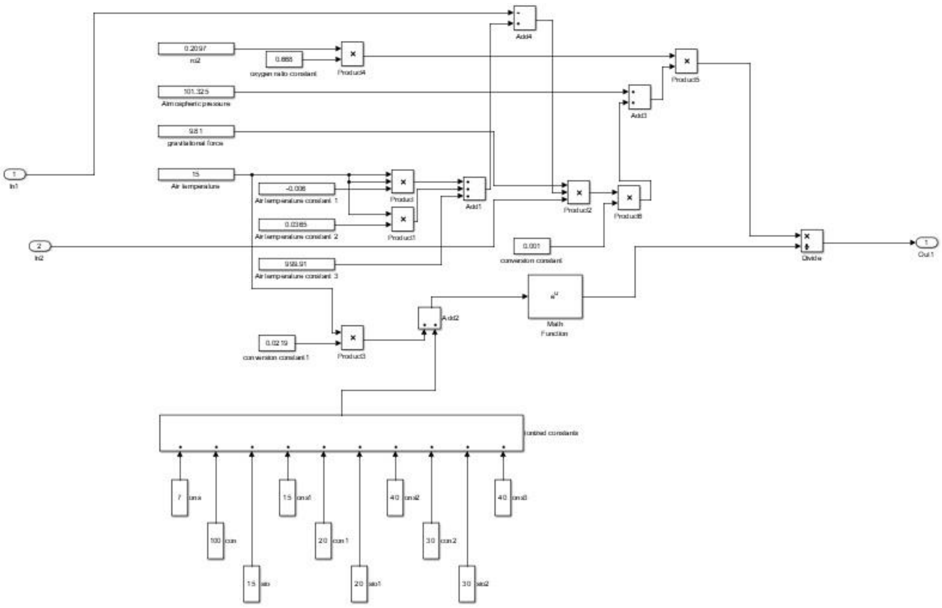

Figure 5.6 Schematization of the WWTP model aeration block

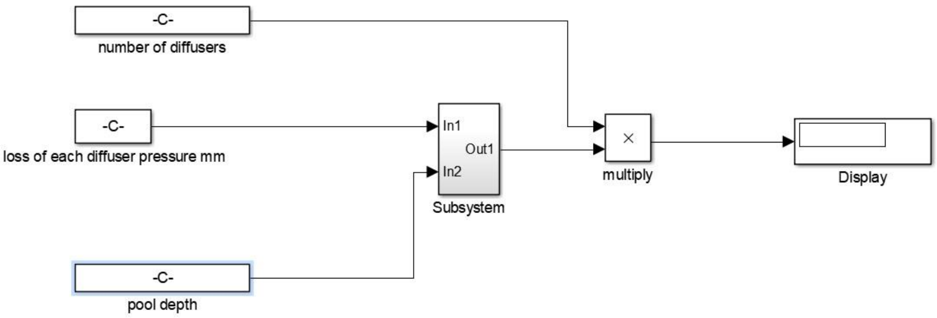

Figure 5.7 Schematization of the WWTP model for aeration system block

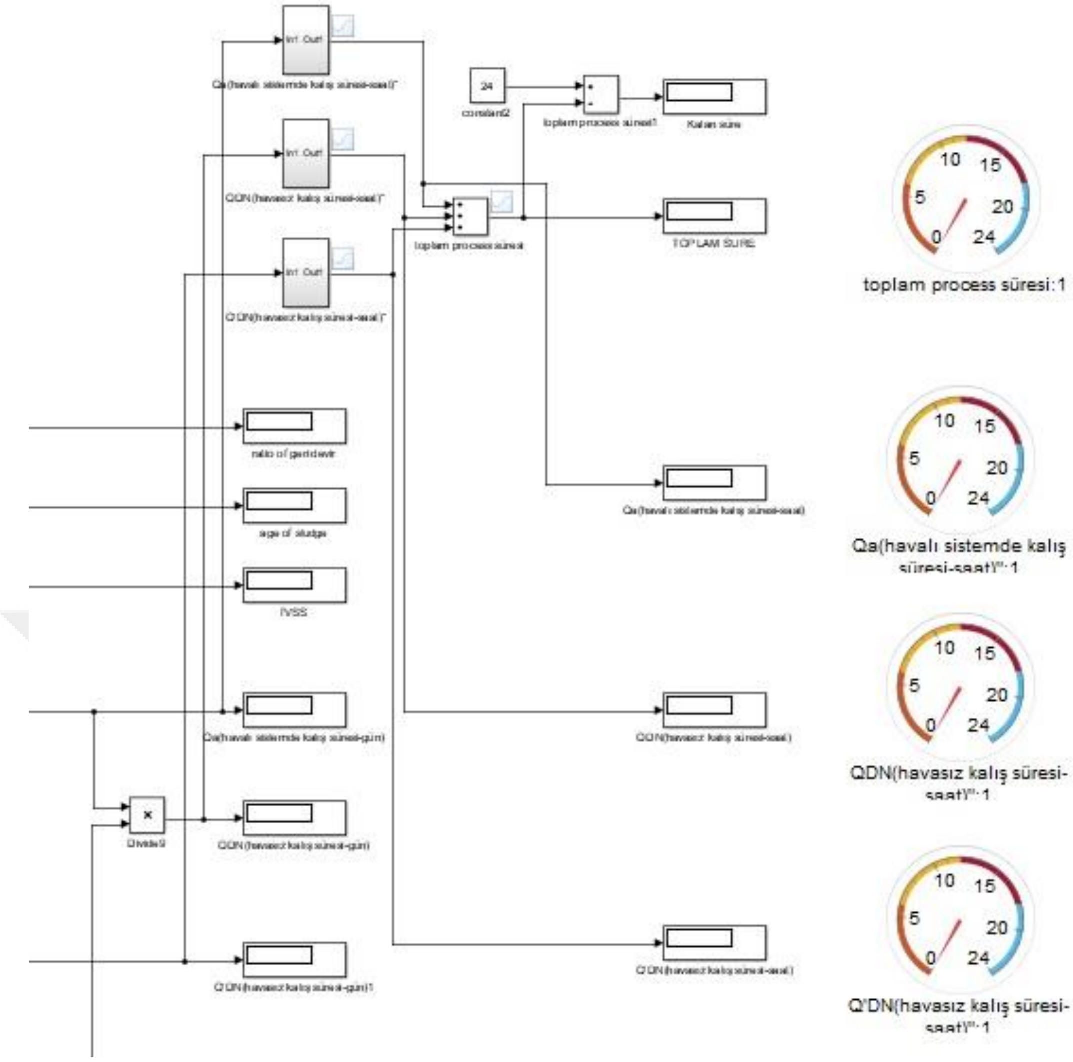

Figure 5.8 Schematization of the WWTP model retention time block

A consistent starting point minimizes the effect on the generated dynamic performance of starting conditions. For steady state conditions, the initial conditions are described as the state of the variables. Therefore, the first step in the simulation process is to simulate the steady state of the system under analysis using constant flow and composition effect.

By simulating 100 days using a constant influent, the steady state is established. For this reason, dry weather data is used. Figure 5.9 shows the efficiency block which is used to obtain a comprehensive efficiency assessment.

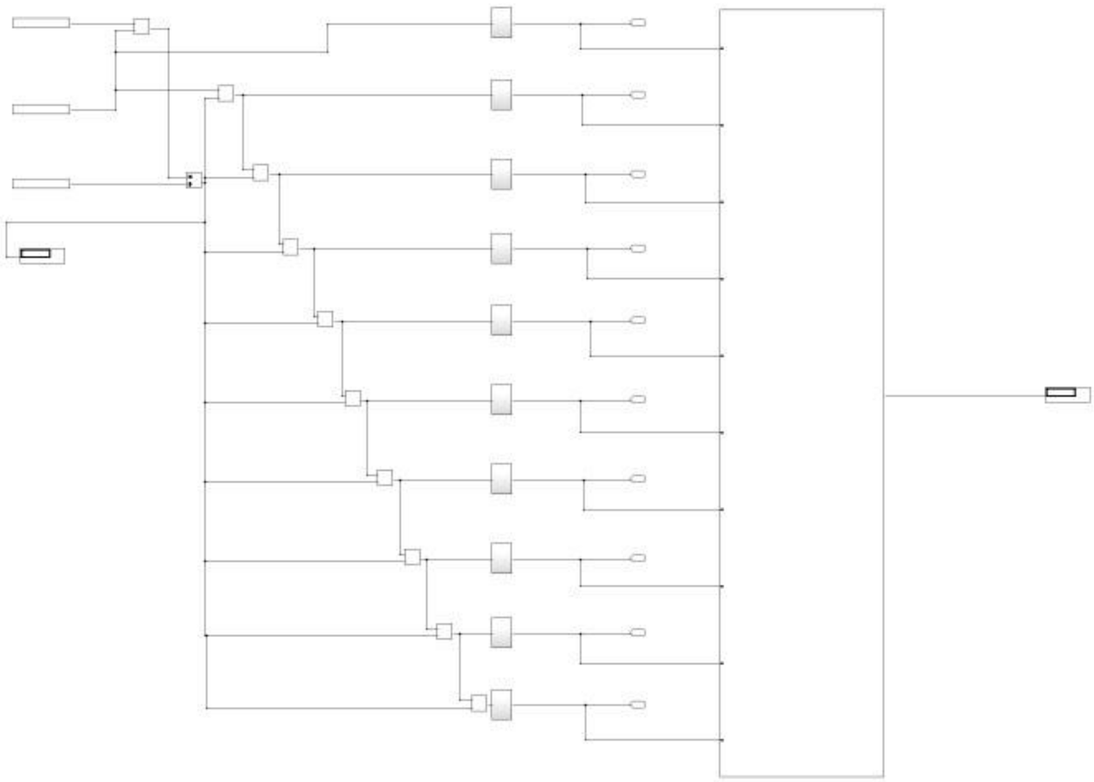

Figure 5.9 Schematization of the WWTP model total efficiency block

As performed in such cases, a mixed identification of the parameters are made, namely a model structure is set up out of the partial knowledge of the process and the parameters of the model are experimentally determined as shown in Figure 4.5.

Within such an approach, the analytical identification provides information prior to the experimental identification procedure by means of which the parameters are estimated. This modelling manner is realistic and blends the physical comprehension of the process with the experimental determination of certain parameters. Figure 5.1 presents the general computer model corresponding to the classified equations in the previous sections.

CHAPTER VI

CASE STUDY: GAZİANTEP OĞUZELİ WWTP

Computer simulations of UTM have been applied to the Oğuzeli WWTP in Gaziantep province of Turkey. These results are used for validation and comparison purposes in this study.

6.1 Plant Characteristics

Oğuzeli WWTP is located at Gaziantep province in Turkey, projected for 40,000 people with a treatment capacity of 8000 m^3/day [148]. The annual rates in the year of 2019 for influent and effluent flows are depicted in Figure 6.1-a. Annual distribution of influent-effluent characteristics are shown in graphics of Figure 6.1.

Due to seasonal variations in weather conditions, some fluctuations can be observed as shown in Figure 6.2, which indicates DO concentrations in oxidation pool during a typical winter day (December 1st), and a typical summer day (1st of July).

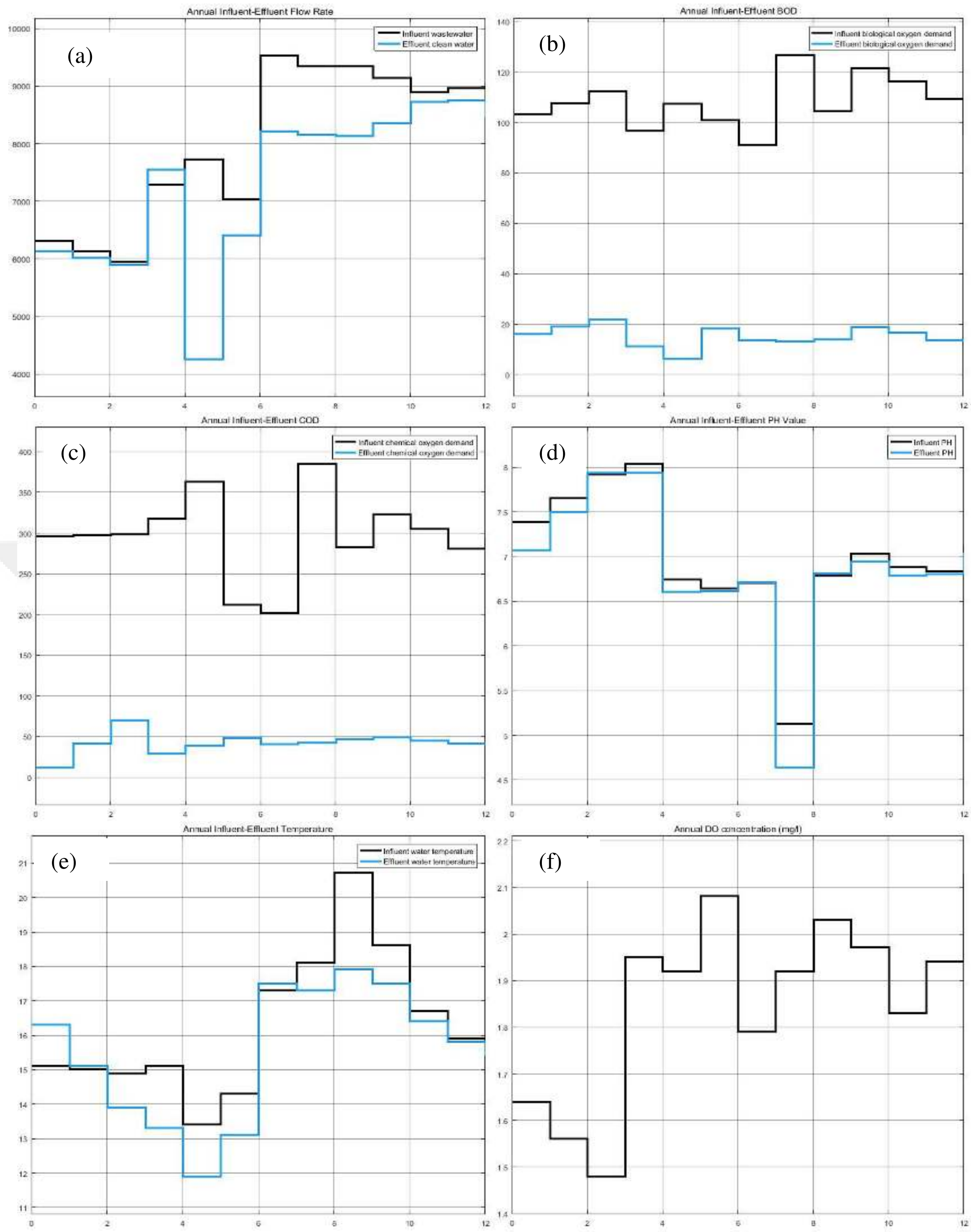

Figure 6.1 Annual influent-effluent characteristics of Oğuzeli WWTP a) influent-effluent flow rate, b) influent-effluent BOD, c) influent-effluent COD, d) influent-effluent pH, e) influent-effluent water temperature, f) Annual DO concentration

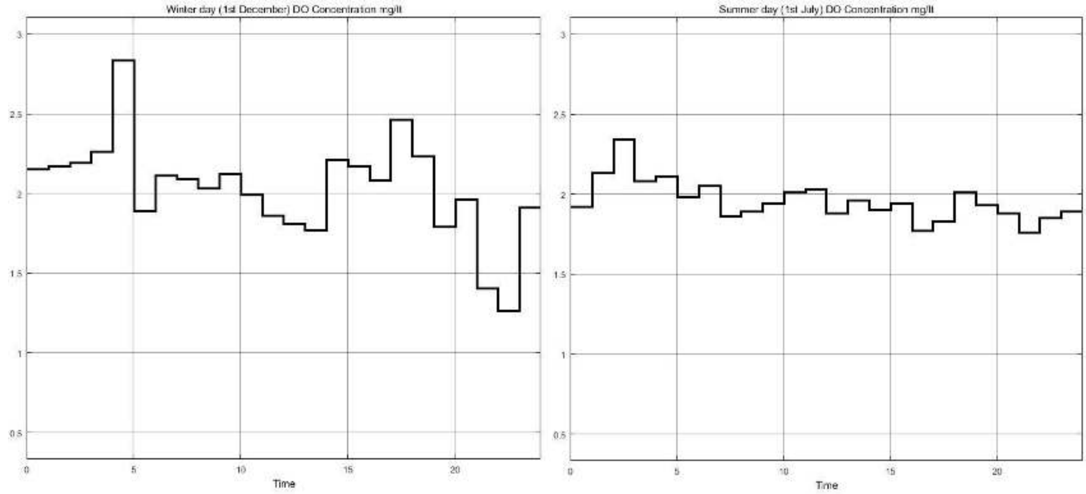

Figure 6.2 Dissolved oxygen characteristics on a winter day (December 1st, left), and a summer day (July 1st, right)

6.2 Simulation Test Results

Numerical simulations are implemented on a daily scale for short-term tests and annual scale for long-term tests. The accuracy of the system and the worst case scenario are observed in daily simulations, while it is possible to observe long-term conditions with annual simulations. The results are compared with the data resulting from one-year observations of Oğuzeli WWTP measurements. The daily behavior of DO within the UTM structure, which has a vital role for bacterial life, is simulated first.

6.2.1 Simulation Tests on Existing Plant

The numerical data set of Oğuzeli WWTP influent-effluent characteristics is shown in Table 6.1

Table 6.1 Influent-effluent water characteristics of Oğuzeli WWTP

	Inf. Avg. Flow (m^3/day)	Eff. Avg. Flow (m^3/day)	Inf. pH	Eff. pH	Inf. Temp (˚C)	Eff. Temp (˚C)	Inf. COD (mg/L)	Eff. COD (mg/L)	Inf. BOD (mg/L)	Eff. BOD (mg/L)	DO (mg/L)
Jan	6124	6011	7.65	7.5	15	15.1	296.7	40.85	107.52	18.8	1.56
Feb	5937	5895	7.92	7.93	14.9	13.9	297.6	69.6	112	21.6	1.48
Mar	7283	7547	8.03	7.93	15.1	13.3	316.8	28.8	96.53	11.2	1.95
Apr	7728	4257	6.74	6.6	13.4	11.9	362.3	38.5	107.2	6.3	1.92
May	7031	6403	6.64	6.61	14.3	13.1	211.2	48	100.7	18	2.08
June	9524	8213	6.7	6.71	17.3	17.5	201.5	40.7	91	13.6	1.79
July	9335	8153	5.13	4.64	18.1	17.3	384	41.6	126.3	13	1.92
Aug	9337	8131	6.79	6.81	20.7	17.9	282.2	46	104.2	13.7	2.03
Sep	9135	8356	7.03	6.94	18.6	17.5	322.4	48.6	121.2	18.6	1.97
Oct	8891	8723	6.88	6.79	16.7	16.4	304.5	44.8	116.1	16.4	1.83
Nov	8954	8741	6.83	6.8	15.9	15.8	280.6	41.5	109.2	13.4	1.94
Dec	9067	8467	7.13	7.05	15.5	15.4	294.2	38.7	94.6	13.1	2.13
Ave rage	**8195**	**7408**	**6.95**	**6.85**	**16.3**	**15.4**	**296.16**	**43.9**	**107.2**	**14.8**	**1.88**

Figure 6.3 shows grid system time-scaled in seconds for two different day cycles on December 1st and July 1st and annual behavior of the system as a part of physical treatment. The nonlinear model is simulated to obtain optimal bar thickness and bar intervals in Oğuzeli WWTP.

The experimental results are acquired from the measurements of the nonlinear process of Oğuzeli WWTP. With the purpose of validating the process model used in simulations, system output data obtained from nonlinear model and nonlinear plant output measurements are compared. Figures 6.4 and 6.5 show the performance of the optimized (WOA) grid system based on the appropriate bar thickness and bar spacing permitted in the literature in Oğuzeli, for the critical two days selected between 1st of December and 1st of July and annually.

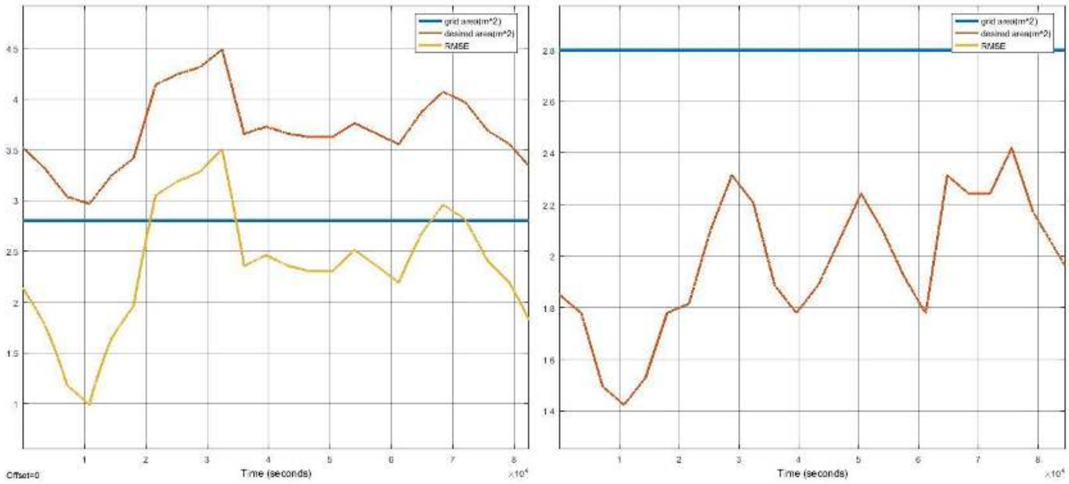

Figure 6.3 Grid simulations for on a winter day (December 1st, left), and a summer day (July 1st, right)

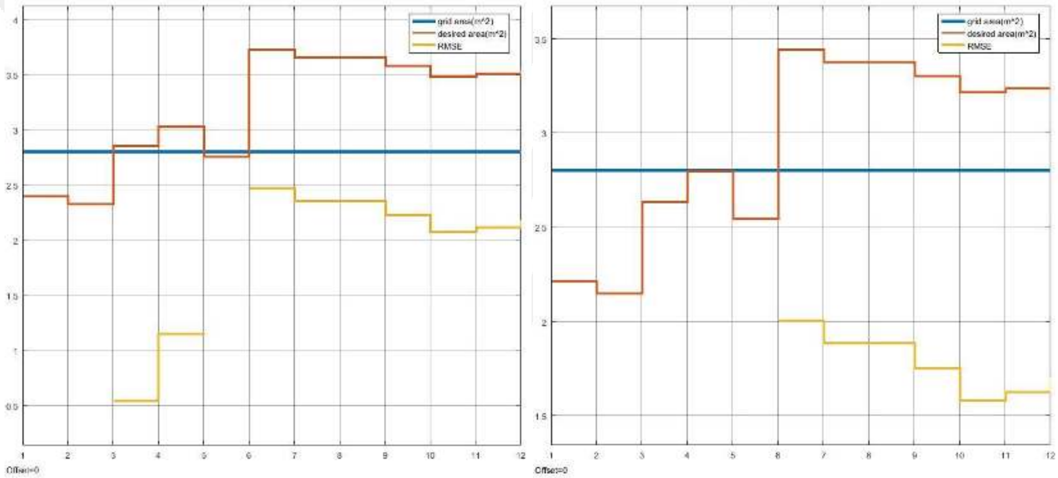

Figure 6.4 Annual existing (left) and optimized (right) grid simulations

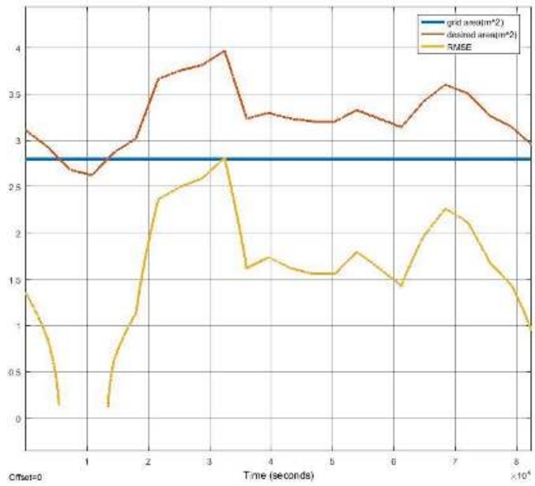

Figure 6.5 Winter day (December 1st) optimized grid simulations

Figures 6.6 and 6.7 provide a comparison of the DO concentration on both traditional method and optimized solution, where the effects are time-scaled in hours on December 1st and July 1st for two separate day cycles. The nonlinear model is simulated with Oğuzeli WWTP to achieve optimum concentration of DO for corresponding parameters.

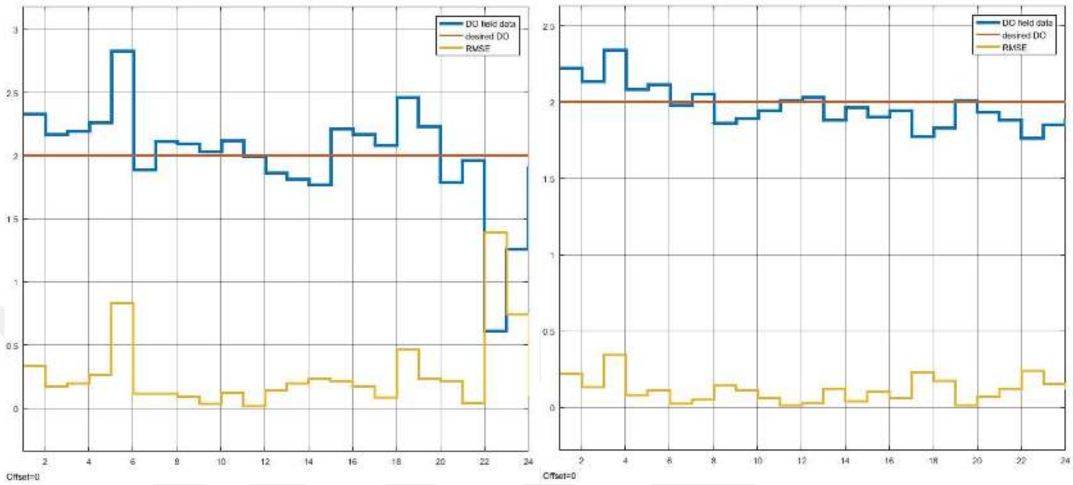

Figure 6.6 DO simulations on a winter day (December 1st, left), and a summer day (July 1st, right)

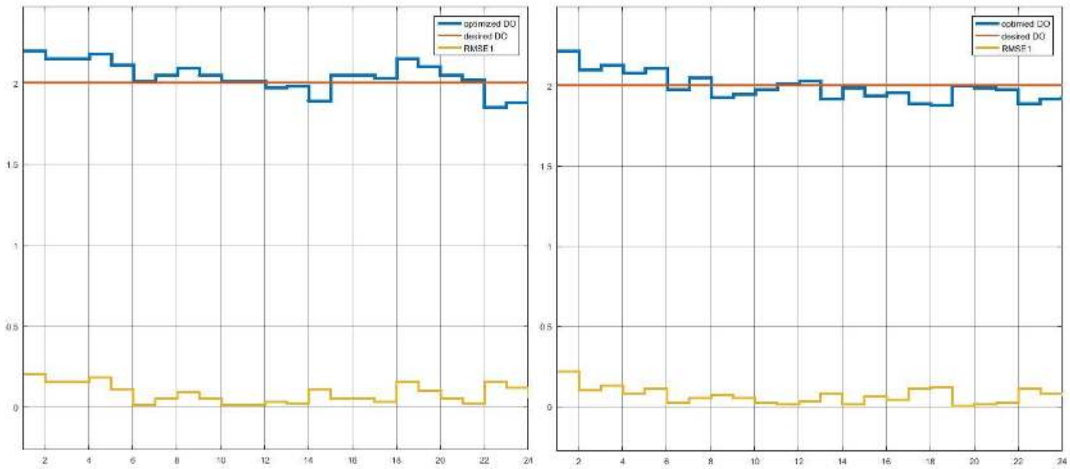

Figure 6.7 DO optimized simulations on a winter day (December 1st, left), and a summer day (July 1st, right)

6.2.2 Simulation Tests on Proposed UTM Design

Figure 6.7 shows the comparison of the DO concentration on both conventional system and proposed UTM, where the results are time-scaled in seconds for two different day cycles on December 1st and July 1st. The nonlinear model is simulated to obtain optimal DO concentration for equivalent UTM parameters with Oğuzeli WWTP. The experimental results are acquired from the measurements of the nonlinear process of Oğuzeli WWTP. With the purpose of validating the process model used in simulations, system output data obtained from nonlinear model and nonlinear plant output measurements are compared. In Figure 6.8, for the selected critical two days of December 1st and July 1st, the optimal solution shows the cycle performance in Oğuzeli WWTP.

There are 500 iterations performed for each cycle depending on the influent and effluent water characteristics which drives blower frequency. In nonlinear model of UTM, water characteristics cause changes on anaerobic and aerobic durations. The best solution around the set point of 2 mg O_2/l is taken into consideration for these procedures. As shown in Figure 6.8, DO concentration reaches the peak value of just over 2 mg O_2/l for both critical days of summer and winter to perform aerobic phases properly, providing sufficient oxidation duration for living bacteria. After a while the anaerobic phase starts for sedimentation and retention. At the end of the period, durations and the upper and lower limits are redefined with 500 iterations for the next cycle involving aerobic and anaerobic phases to obtain a new optimal solution.

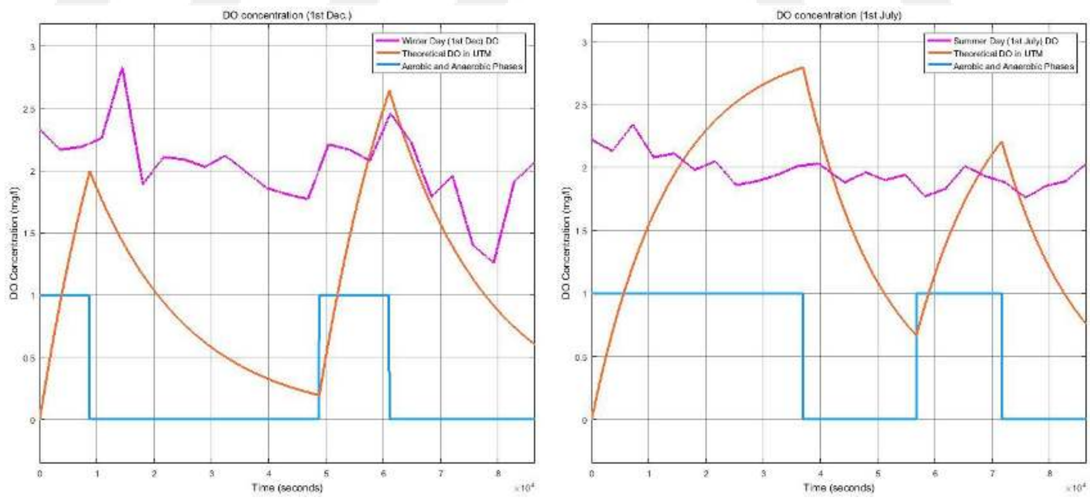

Figure 6.8 Dissolved oxygen simulation in UTM on a winter day (December 1st, left), and a summer day (July 1st, right)

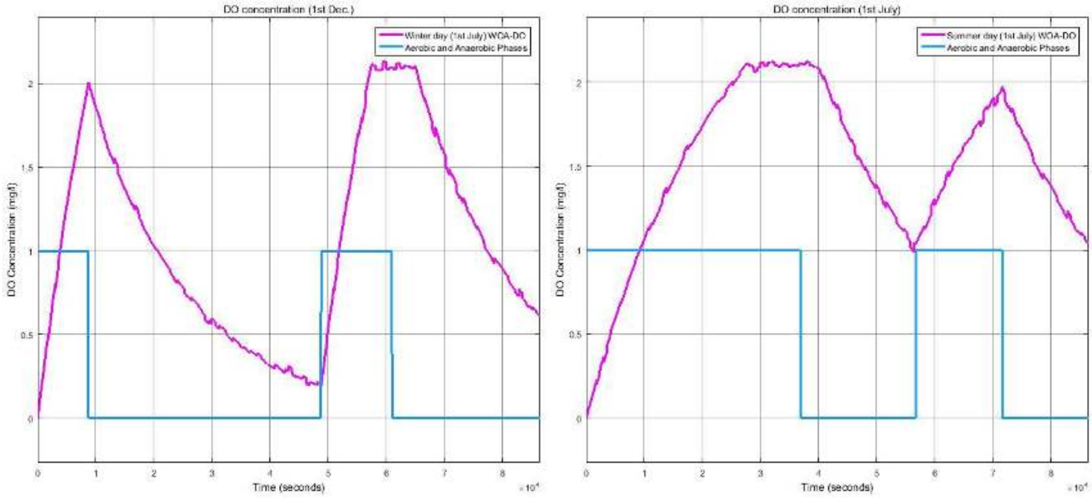

Figure 6.9 Optimized aeration system behavior in UTM on a winter day (December 1st, left), and a summer day (July 1st, right)

The comparison of the theoretical behaviors of the UTM with the conventional solution without optimization presented in Figure 6.9 and whale optimized solution in Figure 6.8 shows that the curve of DO concentration varies significantly. The variable frequency controlled blower units control this optimized behavior. Moreover, one can observe in the latter figure that the relatively long aeration phases are shifted towards the right. This provides another optimal solution which is for realizing enough aeration duration for relatively long intervals.

Figure 6.8 and 6.9 depict the variation of DO concentrations for the critical two days of with respect to time t. However, the amount of oxygen in the tank is fluctuated along the anaerobic and aerobic time intervals as we have observed and simulated for the one year period. Similar to the whale feeding behavior, which is based on preying in shrinking circles and according position updates the optimization of UTM has been focused on two aspects of aeration duration, and reaching to the desired value that is 2 mg O_2/l. In order to indicate and assess the performance of the UTM for both aspects of aeration duration and DO tracking error in optimized and conventional designs, the Root Mean Square Error (RMSE) index given by the following is used,

$$\text{RMSE}=\sqrt{\sum(\text{observed value - desired value})^2/\ (\text{number of samples})} \qquad (6.1)$$

The designed UTM performance and effect of optimization are presented in terms of RMSE index values as summarized in Table 6.4.

Table 6.2 RMSE values for conventional and optimal UTM designs

Parameters	RMSE values		Improvement in RMSE
	conventional	optimal	
t	0.138	0.068	51%
DO	0.236	0.049	79%

As the calculated RMSE index values in Table 6.2 clearly indicate, the time duration of aeration and accuracy of DO variation in the proposed UTM design with WOA optimization are significantly improved. The results for, optimal WOA solution, show good tracking performance with good duration of aeration time in following the desired DO value with good accuracy.

6.3 Summary and Discussions

Screening, DO, Aeration system (Blowers and diffusers are included), secondary sedimentation tracking errors in optimized and actual designs, and the designed simulator performance and effect of optimization are presented in terms of RMSE index values as summarized in Table 6.3-6.4 for the Gaziantep Oğuzeli WWTP.

Table 6.3 RMSE values for simulator and optimal operation conditions in a summer day

Parameters	RMSE values		Improvement in RMSE
	actual	optimal	
Screening	0.157	0.081	51%
DO	0.253	0.192	75%
Aeration System	0.125	0.081	64%
Secondary Sedimentation	0.068	0.053	77%

Table 6.4 RMSE values for simulator and optimal operation conditions in a winter day

Parameters	RMSE values		Improvement in RMSE
	actual	optimal	
Screening	0.057	0.051	89%
DO	0.291	0.192	65%
Aeration System	0.156	0.085	54%
Secondary Sedimentation	0.048	0.040	83%

CHAPTER VII

CONCLUSION

In this thesis, a simulator for WWTP is designed. The simulator has some advantages especially solving optimization problems. Moreover, a novel design for aeration-sedimentation processes in WWTPs is proposed and investigated as a constructive approach. The UTM design for both aeration and sedimentation phases is obtained through optimization, as an alternative for the conventional approach where two separate tanks are used for aeration and sedimentation processes. In this design, the aeration tank is embedded within the main tank with an Archimedean spiral geometry. An optimization problem is defined to find optimal locations of the diffusers in the UTM using WOA method. Optimal design of the proposed UTM for aeration-sedimentation processes is tested via computer simulations to reveal efficacy of the method. Simulation results of a whole system and UTM reveal significant improvement in the operational performance of the WWT system. In order to prove practical value of proposed methods, the WWTP simulator and optimal UTM design obtained through WOA is also tested on the Oğuzeli WWTP as a case study.

Simulation results are compared with real data collected from field measurements in a one-year period. The results show the superiority of the proposed optimal designs compared to the existing models and reveal practical value of the study. As a consequence it is concluded that proposed optimal design of the single-tank structure can be a valuable alternative for modeling, investigation, design and implementation of aeration-sedimentation processes in WWT.

In addition to the forecast and long-short time planning facilities; operation, research and development, performance assessment steps are simulated in a user friendly interface.

7.1 Recommendations for Future Work

Further justification of the method that has been investigated in this research is possible through laboratory-scale experiments and real-time applications on WWT systems, which are planned as future studies.

Different optimization algorithms can be adapted to designed the simulator with comparison studies. It is also possible to use different programming languages for the simulator.

Using different performance indices which also are consider ''time'', conventional PID or more advanced control methods (adaptive, robust) can be designed and developed. This simulator can be used for the control of WWTP in closed loop approach. The simulator can be tested under the closed loop control conditions.

Independently from all the system parameters, system identification method can be used as black box modelling and simulation approach.

REFERENCES

[1] Durning, A. T., & Durning, A. B. (1992). *How much is enough?: the consumer society and the future of the earth*. WW Norton & Company.

[2] T. W. Institute, *State of the World 2007: Our Urban Future*, no. 0. 2007.

[3] Human Rights Watch, *World Report 2018: Events of 2017*. 2018.

[4] Rogowska, J., Cieszynska-Semenowicz, M., Ratajczyk, W., & Wolska, L. (2020). Micropollutants in treated wastewater. *Ambio*, *49*(2), 487-503.

[5] Walton M., "Commentary: The energy sector should care about wastewater," *www.iea.org*.

[6] Chen, X., Al, R., Behera, C. R., & Sin, G. (2018). Process Synthesis, Design, and Control of Wastewater Treatment Plants. In *Reference Module in Chemistry, Molecular Sciences and Chemical Engineering* (pp. 1-14). Elsevier.

[7] Scholzel, H. (1999). Small scale wastewater treatment plant project: Report of visit to the Republic of the Marshall Islands: 3-10 June 1999. *SOPAC Prelim. Rep.*, (114), 31.

[8] Chun, T. S., Malek, M. A., & Ismail, A. R. (2017). A Review of Wastewater Treatment Plant Modelling: Revolution on Modelling Technology. *American Journal of Environmental and Resource Economics*, *2*(1), 22-26.

[9] Jeppson, U., Baky, A., Hellström, D., Jönsson, H., & Kärrman, E. (2005). *The URWARE Wastewater: treatment Plant Models*. Urban Water, Chalmers University of Technology.

[10] Serdarevic, A., & Dzubur, A. (2016). Wastewater process modeling. *Coupled systems mechanics*, *5*(1), 21-39.

[11] Gernaey, K. V., van Loosdrecht, M. C., Henze, M., Lind, M., & Jørgensen, S. B. (2004). Activated sludge wastewater treatment plant modelling and

simulation: state of the art. *Environmental Modelling & Software*, *19*(9), 763-783.

[12] Baeten, J. E., Batstone, D. J., Schraa, O. J., van Loosdrecht, M. C., & Volcke, E. I. (2019). Modelling anaerobic, aerobic and partial nitritation-anammox granular sludge reactors-A review. *Water research*, *149*, 322-341.

[13] Baar, W. (2018). *Control of the Aeration Process in the Biological Treatment of Wastewater* (Doctoral dissertation).

[14] Laizāns, A., & Šnīders, A. (2012). Analytical model and simulation of oxygen solubility in wastewater. " *Renew. Energy Energy Effic.*, pp. 109–114, 2012.

[15] Piotrowski, R., Duzinkiewicz, K., & Brdys, M. A. (2004). Dissolved oxygen tracking and control of blowers at fast time scale. *IFAC Proceedings Volumes*, *37*(11), 281-287.

[16] Hamzah, A. S., Banitalebi, A., Murid, A. H., Aziz, Z. A., Ramli, H., Rahman, H., & Hamdon, N. (2016). A Mathematical Model for Wastewater Treatment Process of an Oxidation Pond. *Jurnal Teknologi*, *78*(3-2).

[17] Yetilmezsoy, K. (2010). Modeling studies for the determination of completely mixed activated sludge reactor volume: Steady-state, empirical and ANN applications. *Neural Network World*, *20*(5), 559.

[18] Santín, I., Barbu, M., Pedret, C., & Vilanova, R. (2019). Dissolved Oxygen Control in Biological Wastewater Treatments with Non-Ideal Sensors and Actuators. *Industrial & Engineering Chemistry Research*, *58*(45), 20639-20654.

[19] Holenda, B., Domokos, E., Redey, A., & Fazakas, J. (2008). Dissolved oxygen control of the activated sludge wastewater treatment process using model predictive control. *Computers & Chemical Engineering*, *32*(6), 1270-1278.

[20] Piotrowski, R. (2016). Comparison of two nonlinear predictive control algorithms for dissolved oxygen tracking problem at wwtp. *Journal of Automation Mobile Robotics and Intelligent Systems*, *10*(1), 8-16.

[21] Santin, I., Pedret, C., & Vilanova, R. (2015). Applying variable dissolved

oxygen set point in a two level hierarchical control structure to a wastewater treatment process. *Journal of Process Control*, *28*, 40-55.

[22] Nelson M. I., Alqahtani, R. T., & Hai, F. I. (2018). Mathematical modelling of the removal of organic micropollutants in the activated sludge process: a linear biodegradation model. *The ANZIAM Journal*, *60*(2), 191-229.

[23] Petersen, B., Gernaey, K., Henze, M., & Vanrolleghem, P. A. (2003). Calibration of activated sludge models: A critical review of experimental designs. In *Biotechnology for the environment: Wastewater treatment and modeling, waste gas handling* (pp. 101-186). Springer, Dordrecht.

[24] Gujer, W., Henze, M., Mino, T., Matsuo, T., Wentzel, M. C., & Marais, G. V. R. (1995). The activated sludge model No. 2: biological phosphorus removal. *Water science and technology*, *31*(2), 1-11.

[25] Lemoine, C., & Steyer, J. P. Multiobjective Genetic Algorithms for the Optimisation of Wastewater Treatment Processes.

[26] Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M. C., Marais, G. V. R., & Van Loosdrecht, M. C. (1999). Activated sludge model no. 2d, ASM2d. *Water Science and Technology*, *39*(1), 165-182.

[27] Ráduly, B., Capodaglio, A. G., & Vaccari, D. A. (2015). Empirical Modelling Of Wastewater Treatment Processes—An Approach to Model Reduction and Integration.

[28] Henze, M., Gujer, W., Mino, T., & van Loosdrecht, M. C. (2000). *Activated sludge models ASM1, ASM2, ASM2d and ASM3*. IWA publishing.

[29] Mirjalili, S., Saremi, S., Mirjalili, S. M., & Coelho, L. D. S. (2016). Multi-objective grey wolf optimizer: a novel algorithm for multi-criterion optimization. *Expert Systems with Applications*, *47*, 106-119.

[30] Mirjalili, S. (2016). Dragonfly algorithm: a new meta-heuristic optimization technique for solving single-objective, discrete, and multi-objective problems. *Neural Computing and Applications*, *27*(4), 1053-1073.

[31] Fleury, C., & Braibant, V. (1984). Optimization Methods. In *Computer Aided*

Analysis and Optimization of Mechanical System Dynamics (pp. 637-678). Springer, Berlin, Heidelberg.

[32] Hamed, M. M., Khalafallah, M. G., & Hassanien, E. A. (2004). Prediction of wastewater treatment plant performance using artificial neural networks. *Environmental Modelling & Software*, *19*(10), 919-928.

[33] "SIMBA Home Page, http://www.inctrl.ca/software/simba." .

[34] "WEST Home Page, https://www.mikepoweredbydhi.com/ products/west." .

[35] "BIOWIN Home Page, http://envirosim.com/products/biowin." .

[36] "GPSX https://www.hydromantis.com/GPSX.html." .

[37] Kuş, B. A., & Kara, T. (2020). Modeling and simulation of an optimal unified tank model for aeration-sedimentation processes in wastewater treatment plants. *Journal of Water Process Engineering*, *37*, 101487.

[38] Cuevas, E., Gonzalez, M., Zaldivar, D., Perez-Cisneros, M., & García, G. (2012). An algorithm for global optimization inspired by collective animal behavior. *Discrete Dynamics in Nature and Society*, *2012*.

[39] Hain, J. H. W., Carter, G. R., Kraus, S. C., Mayo, C. A., & Winn, H. E. (1982). Feeding behavior of the humpback whale, Megaptera novaeangliae, in the western North Atlantic [North Eastern States (USA)]. *Fishery bulletin United States, National Marine Fisheries Service*.

[40] Mirjalili, S., & Lewis, A. (2016). The whale optimization algorithm. *Advances in engineering software*, *95*, 51-67.

[41] Miry, A. H., Mary, A. H., & Miry, M. H. (2019, May). Improving of Maximum Power Point Tracking for Photovoltaic Systems Based on Swarm Optimization Techniques. In *IOP Conference Series: Materials Science and Engineering* (Vol. 518, No. 4, p. 042003). IOP Publishing.

[42] Wang, J., Du, P., Niu, T., & Yang, W. (2017). A novel hybrid system based on a new proposed algorithm—Multi-Objective Whale Optimization Algorithm for wind speed forecasting. *Applied energy*, *208*, 344-360.

[43] Oliva, D., Abd El Aziz, M., & Hassanien, A. E. (2017). Parameter estimation of photovoltaic cells using an improved chaotic whale optimization algorithm. *Applied Energy*, *200*, 141-154.

[44] Abdel-Basset, M., Manogaran, G., El-Shahat, D., & Mirjalili, S. (2018). A hybrid whale optimization algorithm based on local search strategy for the permutation flow shop scheduling problem. *Future Generation Computer Systems*, *85*, 129-145.

[45] Beraud, B. (2009). *Methodology for the optimization of wastewater treatment plant control laws based on modeling and multi-objective genetic algorithms* (Doctoral dissertation).

[46] Cooper, P. F. (2001). Historical aspects of wastewater treatment. *Decentralised Sanitation and Reuse*.

[47] Grady Jr, C. L., Daigger, G. T., Love, N. G., & Filipe, C. D. (2011). *Biological wastewater treatment*. CRC press.

[48] Tchobanoglous, G., Theisen, H., & Vigil, S. (1993). *Integrated solid waste management: Engineering principles and management lssues*. McGraw-Hill.

[49] Jeppsson, U. (1996). *Modelling aspects of wastewater treatment processes* (p. 428). Sweden: Lund Institute of Technology.

[50] Stanwell-Smith, R. (2010). Public toilets down the drain? Why privies are a public health concern. *Public Health*, *124*(11), 613-616.

[51] Mackintosh, A. (1873). Craigentinny Meadows near Edinburgh. *British Medical Journal*, *2*(665), 389.

[52] Orhon, D. (2015). Evolution of the activated sludge process: the first 50 years. *Journal of Chemical Technology & Biotechnology*, *90*(4), 608-640.

[53] Ardern, E., & Lockett, W. T. (1914). Experiments on the oxidation of sewage without the aid of filters. *Journal of the society of chemical industry*, *33*(10), 523-539.

[54] Turovskiy, I. S., & Mathai, P. K. (2006). *Wastewater sludge processing*. John

Wiley & Sons.

[55] Alharbi, A. O. M. (2016). The biological treatment of wastewater: mathematical models. *Bulletin of the Australian Mathematical Society*, *94*(2), 347-348.

[56] Goodman, B. L., & Englande Jr, A. J. (1974). A unified model of the activated sludge process. *Journal (Water Pollution Control Federation)*, 312-332.

[57] Metcalf, L., Eddy, H. P., & Tchobanoglous, G. (1979). *Wastewater engineering: treatment, disposal, and reuse* (Vol. 4). New York: McGraw-Hill.

[58] Li, R. Y., Zhang, T., & Fang, H. H. (2008). Characteristics of a phototrophic sludge producing hydrogen from acetate and butyrate. *International journal of hydrogen energy*, *33*(9), 2147-2155.

[59] Wehner, J. F., & Wilhelm, R. H. (1956). Boundary conditions of flow reactor. *Chemical engineering science*, *6*(2), 89-93.

[60] Muñoz, R., Köllner, C., & Guieysse, B. (2009). Biofilm photobioreactors for the treatment of industrial wastewaters. *Journal of hazardous materials*, *161*(1), 29-34.

[61] Radjenović, J., Matošić, M., Mijatović, I., Petrović, M., & Barceló, D. (2007). Membrane bioreactor (MBR) as an advanced wastewater treatment technology. In *Emerging Contaminants from Industrial and Municipal Waste* (pp. 37-101). Springer, Berlin, Heidelberg.

[62] Pomies, M., Choubert, J. M., Wisniewski, C., & Coquery, M. (2013). Modelling of micropollutant removal in biological wastewater treatments: a review. *Science of the Total Environment*, *443*, 733-748.

[63] Goswami, L., Kumar, R. V., Borah, S. N., Manikandan, N. A., Pakshirajan, K., & Pugazhenthi, G. (2018). Membrane bioreactor and integrated membrane bioreactor systems for micropollutant removal from wastewater: a review. *Journal of water process engineering*, *26*, 314-328.

[64] Kay, L. G., Brouckaert, C. J., & Sindall, R. C. (2019). Modelling mesophilic-thermophilic temperature transitions experienced by an aerobic membrane bioreactor treating furfural plant effluent. *Water SA*, *45*(3), 317-328.

[65] Khan, S. J., Hasnain, G., Fareed, H., & Aim, R. B. (2019). Evaluation of treatment performance of a full-scale membrane bioreactor (MBR) plant from unsteady to steady state condition. *Journal of Water Process Engineering*, *30*, 100379.

[66] Metcalf and Eddy, Inc, Asano, T., Burton, F. L., Leverenz, H., Tsuchihashi, R., & Tchobanoglous, G. (2007). *Water reuse*. McGraw-Hill Professional Publishing.

[67] Kowalik, R., Gawdzik, J., Gawdzik, A., & Gawdzik, B. (2019). Innovative sequential batch reactor solutions for wastewater treatment (Innowacyjne rozwiązania sekwencyjnych reaktorów porcjowych stosowane w oczyszczaniu ścieków). *Structure & Environment*, *11*(2), 141-152.

[68] Lefebvre, O., & Moletta, R. (2006). Treatment of organic pollution in industrial saline wastewater: a literature review. *Water research*, *40*(20), 3671-3682.

[69] Jakubaszek, A., & Stadnik, A. (2018). Efficiency of Sewage Treatment Plants in the Sequential Batch Reactor. *Civil and Environmental Engineering Reports*, *28*(3), 121-131.

[70] Olsson, G., Carlsson, B., Comas, J., Copp, J., Gernaey, K. V., Ingildsen, P., ... & Steyer, J. P. (2014). Instrumentation, control and automation in wastewater–from London 1973 to Narbonne 2013. *Water Science and Technology*, *69*(7), 1373-1385.

[71] Hill Jr, C. G. (1977). Basic concepts in reactor design and ideal reactor models. *An introduction to chemical engineering kinetics and reactor design. John Wiley & Sons, New York, NY*, 245-316.

[72] Barber, W. P., & Stuckey, D. C. (1999). The use of the anaerobic baffled reactor (ABR) for wastewater treatment: a review. *Water Research*, *33*(7), 1559-1578.

[73] Sinha, S. K., Sinha, V. K., Pandey, S. K., & Tiwari, A. (2014). A study on the waste water treatment technology for steel industry: recycle and reuse. *Am J Eng Res*, *3*(4), 309-315.

[74] Ekama, G. A., Dold, P. L., & Marais, G. V. R. (1986). Procedures for determining influent COD fractions and the maximum specific growth rate of heterotrophs in activated sludge systems. *Water Science and Technology*, *18*(6), 91-114.

[75] Caraman, S., Sbarciog, M., & Barbu, M. (2007). Predictive Control of aWastewater Treatment Process. *International Journal of Computers Communications & Control*, *2*(2), 132-142.

[76] Shen, W., Chen, X., & Corriou, J. P. (2008). Application of model predictive control to the BSM1 benchmark of wastewater treatment process. *Computers & Chemical Engineering*, *32*(12), 2849-2856.

[77] Vanhooren, H., Meirlaen, J., Amerlinck, Y., Claeys, F., Vangheluwe, H., & Vanrolleghem, P. A. (2003). WEST: modelling biological wastewater treatment. *Journal of Hydroinformatics*, *5*(1), 27-50.

[78] Rivas, A., Irizar, I., & Ayesa, E. (2008). Model-based optimisation of wastewater treatment plants design. *Environmental Modelling & Software*, *23*(4), 435-450.

[79] Shen, W., Chen, X., Pons, M. N., & Corriou, J. P. (2009). Model predictive control for wastewater treatment process with feedforward compensation. *Chemical Engineering Journal*, *155*(1-2), 161-174.

[80] Juan, Y. K., Gao, P., & Wang, J. (2010). A hybrid decision support system for sustainable office building renovation and energy performance improvement. *Energy and buildings*, *42*(3), 290-297.

[81] Urena, F., Alfaro, V. M., Arrieta, O., & Vilanova, R. (2011, April). MATLAB based graphical interface simulator for wastewater treatment plant control by using the benchmark BSM1. In *2011 IEEE Global Engineering Education Conference (EDUCON)* (pp. 585-591). IEEE.

[82] Lee, D. S., Jeon, C. O., Park, J. M., & Chang, K. S. (2002). Hybrid neural network modeling of a full-scale industrial wastewater treatment process. *Biotechnology and bioengineering*, *78*(6), 670-682.

[83] Lee, Y., Cho, J., Seo, Y., Lee, J. W., & Ahn, K. H. (2002). Modeling of submerged membrane bioreactor process for wastewater treatment. *Desalination*, *146*(1-3), 451-457.

[84] Olsson, G., & Newell, B. (1999). *Wastewater treatment systems*. IWA publishing.

[85] Stare, A., Hvala, N., & Vrečko, D. (2006). Modeling, identification, and validation of models for predictive ammonia control in a wastewater treatment plant—a case study. *ISA transactions*, *45*(2), 159-174.

[86] Schönhart, M., Schauppenlehner, T., Schmid, E., & Muhar, A. (2011). Integration of bio-physical and economic models to analyze management intensity and landscape structure effects at farm and landscape level. *Agricultural Systems*, *104*(2), 122-134.

[87] Bye, C. M., Jones, R. M., & Dold, P. L. (2012). Modeling the Potential Impact of Sludge Pre-treatment Technologies. *Proceedings of the Water Environment Federation*, *2012*(16), 1025-1026.

[88] G. Started, "Getting Started Tutorial," 2014.

[89] Hauth, J. (2008). Grey-box modelling for nonlinear systems.

[90] Barbu, M., & Caraman, S. (2011). *QFT robust control of wastewater treatment processes*. INTECH Open Access Publisher.

[91] Patry, G. G., & Chapman, D. T. (1989). *Dynamic modeling and expert systems in wastewater engineering*. CRC Press, Inc..

[92] Renganathan, K., & Bhaskar, V. (2012). Performance evaluation and model checking in systems modeled as Hybrid Petri nets. *Applied Mathematical Modelling*, *36*(8), 3941-3947.

[93] Vats, M. C., & Singh, S. K. (2014). E-Waste characteristic and its disposal. *International Journal of ecological science and environmental engineering*, *1*(2), 49-61.

[94] Suresh, S. S., Bonda, S., Mohanty, S., & Nayak, S. K. (2018). A review on

computer waste with its special insight to toxic elements, segregation and recycling techniques. *Process Safety and Environmental Protection*, *116*, 477-493.

[95] Belgiorno, V., Rizzo, L., Fatta, D., Della Rocca, C., Lofrano, G., Nikolaou, A., ... & Meric, S. (2007). Review on endocrine disrupting-emerging compounds in urban wastewater: occurrence and removal by photocatalysis and ultrasonic irradiation for wastewater reuse. *Desalination*, *215*(1-3), 166-176.

[96] Rajasulochana, P., & Preethy, V. (2016). Comparison on efficiency of various techniques in treatment of waste and sewage water–A comprehensive review. *Resource-Efficient Technologies*, *2*(4), 175-184.

[97] Çakmakçı, M., Özkaya, B., Yetilmezsoy, K., & Demir, S. (2013). Su arıtma tesislerinin tasarım ve işletme esasları. *Su Uygunsuzluğu Yönetimi Eğitim Toplantısı, Antalya*, 3-5.

[98] Hahn, H. H., Hoffmann, E., & Ødegaard, H. (Eds.). (2002). *Chemical water and wastewater treatment VII*. IWA publishing.

[99] Sincero, A. P., & Sincero, G. A. (2002). *Physical-chemical treatment of water and wastewater*. CRC press.

[100] Orhon, D., Allı, B., & Sözen, S. (2019). Which activated sludge configurations qualify for maximizing energy conservation–Why?. *Journal of Chemical Technology & Biotechnology*, *94*(2), 556-568.

[101] Heusch, S., Kamradt, B., & Ostrowski, M. (2010). Simulation of wastewater treatment plant within integrated urban wastewater models. *Water Science and Technology*, *61*(10), 2645-2652.

[102] Szilveszter, S., Ráduly, B., Ábrahám, B., Lányi, S., & Niculae, D. R. (2010). Mathematical models for domestic biological wastewater treatment process. *Environmental Engineering and Management Journal*, *9*(5), 629-636.

[103] Hauser, B. (1996). *Practical manual of wastewater chemistry*. CRC Press.

[104] Velez Quintero, C. A. (2012). *Optimization of urban wastewater systems using model based design and control*. IHE Delft Institute for Water Education.

[105] Guocheng, Z., Huaili, Z., Peng, Z., Shaojie, J., Jiangya, M., & Wenyuan, C. (2011, January). Decision model for optimization of coagulation/flocculation process for wastewater treatment. In *2011 Third International Conference on Measuring Technology and Mechatronics Automation* (Vol. 1, pp. 821-826). IEEE.

[106] Marrot, B., Barrios-Martinez, A., Moulin, P., & Roche, N. (2004). Industrial wastewater treatment in a membrane bioreactor: a review. *Environmental progress*, *23*(1), 59-68.

[107] Pokhrel, D., & Viraraghavan, T. (2004). Treatment of pulp and paper mill wastewater—a review. *Science of the total environment*, *333*(1-3), 37-58.

[108] Stypka, A. (1998). Advanced wastewater treatment. *Factors Influencing Sludge Settling Parameters and Solids Flux in the Activated Sludge Process: A Literature Review*.

[109] GÜNDÜZ, Ç. (2009). *Ultrasonic disintegration of sewage sludge* (Doctoral dissertation, DEÜ Fen Bilimleri Enstitüsü).

[110] Nelson, M. I., & Sidhu, H. S. (2009). Analysis of the activated sludge model (number 1). *Applied Mathematics Letters*, *22*(5), 629-635.

[111] Gogate, P. R., & Pandit, A. B. (2004). A review of imperative technologies for wastewater treatment I: oxidation technologies at ambient conditions. *Advances in Environmental Research*, *8*(3-4), 501-551.

[112] Zinatizadeh, A. A. L., Mohamed, A. R., Abdullah, A. Z., Mashitah, M. D., Isa, M. H., & Najafpour, G. D. (2006). Process modeling and analysis of palm oil mill effluent treatment in an up-flow anaerobic sludge fixed film bioreactor using response surface methodology (RSM). *Water research*, *40*(17), 3193-3208.

[113] Gernaey, K. V., van Loosdrecht, M. C., Henze, M., Lind, M., & Jørgensen, S. B. (2004). Activated sludge wastewater treatment plant modelling and simulation: state of the art. *Environmental Modelling & Software*, *19*(9), 763-783.

[114] Gandomi, A. H., Yang, X. S., Talatahari, S., & Alavi, A. H. (2013). Metaheuristic algorithms in modeling and optimization. *Metaheuristic applications in structures and infrastructures*, 1-24.

[115] Bitam, S., Batouche, M., & Talbi, E. G. (2010, April). A survey on bee colony algorithms. In *2010 ieee international symposium on parallel & distributed processing, workshops and phd forum (ipdpsw)* (pp. 1-8). IEEE.

[116] Mirjalili, S., Mirjalili, S. M., & Lewis, A. (2014). Grey wolf optimizer. *Advances in engineering software*, *69*, 46-61.

[117] Yang, J., Lu, L., Ouyang, W., Gou, Y., Chen, Y., Ma, H., ... & Fang, F. (2017). Estimation of kinetic parameters of an anaerobic digestion model using particle swarm optimization. *Biochemical Engineering Journal*, *120*, 25-32.

[118] De Coninck, R., Magnusson, F., Åkesson, J., & Helsen, L. (2016). Toolbox for development and validation of grey-box building models for forecasting and control. *Journal of Building Performance Simulation*, *9*(3), 288-303.

[119] Madsen, H. Statistical modelling of physical systems-an introduction to grey box modelling.

[120] Langergraber, G., Rieger, L., Winkler, S., Alex, J., Wiese, J., Owerdieck, C., ... & Maurer, M. (2004). A guideline for simulation studies of wastewater treatment plants. *Water Science and Technology*, *50*(7), 131-138.

[121] Nuhoglu, A., Keskinler, B., & Yildiz, E. (2005). Mathematical modelling of the activated sludge process—the Erzincan case. *Process Biochemistry*, *40*(7), 2467-2473.

[122] Görgün, E., Insel, G., Artan, N., & Orhon, D. (2007). Model evaluation of temperature dependency for carbon and nitrogen removal in a full-scale activated sludge plant treating leather-tanning wastewater. *Journal of Environmental Science and Health, Part A*, *42*(6), 747-756.

[123] Ni, B. J., Yu, H. Q., & Sun, Y. J. (2008). Modeling simultaneous autotrophic and heterotrophic growth in aerobic granules. *Water Research*, *42*(6-7), 1583-1594.

[124] Yu, J. J., Gu, G. W., Esposito, G., Fabbricino, M., Wang, S. P., & Sun, L. P. (2010). Determination of textile dyeing wastewater COD components by comparison with respirometry and full-scale data. *Environmental technology*, *31*(11), 1191-1201.

[125] Ni, B. J., Xie, W. M., Chen, Y. P., Fang, F., Liu, S. Y., Ren, T. T., ... & Tian, Y. C. (2011). Heterotrophs grown on the soluble microbial products (SMP) released by autotrophs are responsible for the nitrogen loss in nitrifying granular sludge. *Biotechnology and bioengineering*, *108*(12), 2844-2852.

[126] Tiehm, A., Nickel, K., & Neis, U. (1997). The use of ultrasound to accelerate the anaerobic digestion of sewage sludge. *Water science and technology*, *36*(11), 121-128.

[127] Pai, T. Y., Wang, S. C., Lo, H. M., Chen, L., Wan, T. J., Lin, M. R., ... & Lu, T. H. (2017). A simulation of sewer biodeterioration by analysis of different components with a model approach. *International Biodeterioration & Biodegradation*, *125*, 37-44.

[128] Leslie Grady Jr, C. P., Gujer, W., Henze, M., Marais, G. V. R., & Tomonori, M. (1986). A model for single-sludge wastewater treatment systems. *Water science and technology*, *18*(6), 47-61.

[129] Hauduc, H., Rieger, L., Oehmen, A., Van Loosdrecht, M. C. M., Comeau, Y., Héduit, A., ... & Gillot, S. (2013). Critical review of activated sludge modeling: state of process knowledge, modeling concepts, and limitations. *Biotechnology and Bioengineering*, *110*(1), 24-46.

[130] Carrette, R., Bixio, D., Thoeye, C., & Ockier, P. (2001). Full-scale application of the IAWQ ASM No. 2d model. *Water science and technology*, *44*(2-3), 17-24.

[131] Torfs, E., Vlasschaert, P., Amerlinck, Y., Bürger, R., Diehl, S., Farås, S., & Nopens, I. (2013). Towards improved 1-D settler modelling: calibration of the Bürger model and case study. In *86th Annual Water Environment Federation Technical Exhibition and Conference (WEFTEC 2013)*. Water Environment

Federation (WEF).

[132] Bürger, R., Diehl, S., Farås, S., & Nopens, I. (2012). On reliable and unreliable numerical methods for the simulation of secondary settling tanks in wastewater treatment. *Computers & Chemical Engineering*, *41*, 93-105.

[133] Titarev, V. A., & Toro, E. F. (2002). ADER: Arbitrary high order Godunov approach. *Journal of Scientific Computing*, *17*(1-4), 609-618.

[134] Bürger, R., Diehl, S., & Nopens, I. (2011). A consistent modelling methodology for secondary settling tanks in wastewater treatment. *Water research*, *45*(6), 2247-2260.

[135] De Clercq, J., Jacobs, F., Kinnear, D. J., Nopens, I., Dierckx, R. A., Defrancq, J., & Vanrolleghem, P. A. (2005). Detailed spatio-temporal solids concentration profiling during batch settling of activated sludge using a radiotracer. *Water research*, *39*(10), 2125-2135.

[136] Concha, F., & Bustos, M. C. (1992). Settling velocities of particulate systems, 7. Kynch sedimentation processes: continuous thickening. *International journal of mineral processing*, *34*(1-2), 33-51.

[137] K. Yetilmezsoy, (2016). A new simple model for the prediction of waste sludge flow rate in the steady-state completely mixed activated sludge process, *Environ. Eng. Manag. J.*, vol. 15, no. 12, pp. 2613–2630, 2016.

[138] Spellman, F. R. (2014). *Mathematics Manual for Water and Wastewater Treatment Plant Operators-Three Volume Set*. CRC Press.

[139] Qasim, S. R. (2017). *Wastewater treatment plants: planning, design, and operation*. Routledge.

[140] Lozano Avilés, A. B., del Cerro Velázquez, F., & Llorens Pascual del Riquelme, M. (2019). Methodology for Energy Optimization in Wastewater Treatment Plants. Phase I: Control of the Best Operating Conditions. *Sustainability*, *11*(14), 3919.

[141] Olsson, G., & Newel, B. (1999). Modelling, Diagnostic and Control.

[142] Özturan, M., Bozanta, A., Basarir-Ozel, B., Akar, E., & Coşkun, M. (2015). A roadmap for an integrated university information system based on connectivity issues: Case of Turkey. *The International Journal of Management Science and Information Technology (IJMSIT)*, (17), 1-22.

[143] Piotrowski, R., Brdys, M. A., & Miotke, D. (2010). Centralized dissolved oxygen tracking at wastewater treatment plant: Nowy Dwor Gdanski case study. *IFAC Proceedings Volumes*, *43*(8), 292-297.

[144] Nasr, M. S., Moustafa, M. A., Seif, H. A., & El Kobrosy, G. (2011). Modelling and simulation of German BIOGEST/EL-AGAMY wastewater treatment plants–Egypt using GPS-X simulator. *Alexandria Engineering Journal*, *50*(4), 351-357.

[145] Yetilmezsoy, K. (2017). IMECE—Implementation of mathematical, experimental, and computer-based education: A special application of fluid mechanics for civil and environmental engineering students. *Computer Applications in Engineering Education*, *25*(5), 833-860.

[146] Hicks, A., & Slaton, W. (2014). Determining the coefficient of discharge for a draining container. *The Physics Teacher*, *52*(1), 43-47.

[147] T. Kara and B. A. Kuş. (2019). Modelling And Simulation of an Alternative Aeration Process Structure in Wastewater Treatment Plants, *5th International Conference on Engineering & Natural Sciences*, pp. 480–489.

[148] “GASKİ.” [Online]. Available: http://gaski.gov.tr. [Accessed: 03-Mar-2019].

PUBLICATIONS

Indexed Journal Papers

[1] B. A. Kuş and T. Kara, “Modeling and simulation of an optimal unified tank model for aeration-sedimentation processes in wastewater treatment plants,” *J. Water Process Eng.*, vol. 37, p. 101487, Oct. 2020.

Conference Papers and Presentations

[2] Kuş B. Arda, Kara Tolgay, Modelling and Simulation of an Alternative Aeration Process Structure in Wastewater Treatment Plants (Abstract): 5th International Conference on Engineering and Natural Sciences (ISPEC 2019) TÜRKİYE, VAN, 20.12.2019.

[3] Kuş B. Arda, Kara Tolgay, Optimization of Aeration Tank Design for Efficient Operation of Wastewater Treatment Plants: 5th International Conference on Engineering and Natural Sciences (ISPEC 2019) TÜRKİYE, VAN, 20.12.2019.

[4] Kuş Bayram Arda, Kara Tolgay, Wastewater Treatment Plant Modeling and Simulation with Control Purposes: International Conference on Applied Mathematics in Engineering (ICAME’18) TÜRKİYE, Balıkesir, 27.06.2018.

[5] Kara T. & KUŞ B. Arda, “DDS and Speed Optimization Solutions for Enhancement of Operational Efficiency in the City of Gaziantep Urban Railway Transportation System”, International Congress on Advanced Railway Engineering. İstanbul 2015.

[6] Koraşlı C. & Kuş B. Arda ‘Türkiye de Kullanılan Tren Kontrol Sistemlerinin Birleştirilmesi ile Oluşturulması Önerilen Türkiye Tren Kontrol Sistemi (TTKS) Kavramı İçerisinde Bir Alt Sistem Olarak: Yenilikçi Bariyerli Hemzemin Geçit Tasarımı’, 2nd International Symposium on Railway System Engineering. Karabük 2013.

CIRRICULUM VITAE

PERSONAL INFORMATION

Surname, Name: **KUŞ, Bayram Arda**

Date and Place of Birth: 28 June 1985, Gaziantep

Marital Status: Married, 2 Children

e-mail: ardakus@hotmail.com
akus@ilbank.gov.tr

EDUCATION

Degree	Department	Institution
Ph.D.	Electrical & Electronics Engineering	Gaziantep University
MS	Electrical & Electronics Engineering	Gaziantep University
BS	Electrical & Electronics Engineering	Gaziantep University
BS	Public Administration (Open Ed.)	Anadolu University
MPA	Public Administration (Student)	YYÜ

WORK EXPERIENCE

Place	Enrollment	Year
İller Bankası	Technical Specialist	2011-…
Getinsa Ing.	Signaling Engineer	2010-2011
E+M	Signaling & Telecommunication	2009-2010

LANGUAGES

Turkish (Native Language)

English (Excellent)

RESEARCH AND INTEREST AREAS

System quality, fault detection and diagnosis, system simulation and monitoring, optimization, renewable energy, railway signaling and telecommunication, urbanization, biomedical engineering and social engineering.

HOBBIES

Swimming, world music, photography.

MEMBERSHIPS

EMO - Chamber of Electrical Engineers

AWARDS

1- Gaziantep University R&D 2009 Project Competition 1st Prize (2009)

2- Hasan Kalyoncu University, National 5th Energy Summit Project Competition 3rd Prize (2014)