“Dunărea de Jos” University of Galaţi

Doctoral School of Fundamental and Engineering Sciences

PhD THESIS

PhD Thesis Summary

ADVANCED CONTROL STRATEGIES OF WASTEWATER TREATMENT FOR BIOLOGICAL PROCESES

Scientific supervisor,
Professor Sergiu CARAMAN, PhD

PhD candidate,
Eng. Laurențiu LUCA

Series I8: System Engineering No. 6
GALAȚI 2018

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Introduction

It may be said, without doubt, that "water is life". It is a prerequisite for human, animal and plant life, as well as an indispensable resource for the economy. At the same time, water plays a fundamental role in the climate regulation cycle. We all depend on nature for food, air, water, energy and raw materials. Nature and biodiversity make life possible, provide social and health benefits and, last but not least, are the basis of our economy. Healthy ecosystems can help us manage the impact of climate change. However, the natural ecosystems and their vital services are subject to pressure from urban sprawl, intensive farming, pollution, invasive species and climatic change.

The issue of environmental protection and water management is urgent and under the constant attention of the European Union (*EU*). Thus, the European Commission's website, http://ec.europa.eu/environment/water/index_en.htm, lists numerous laws (directives) that bear testimony of the concern of this European Forum as to preventing the environmental degradation and the quality of water resources [1].

The fundamental objective of the *EU* regarding biodiversity strategy is to improve the quality of the environment, protect human health, use natural resources prudently and rationally and promote international level measures that address global or regional environmental issues. To this effect, other areas such as agriculture, energy, transport, fisheries, regional development, research, innovation and foreign aid must to take into account the environmental consequences of policies and related financing decisions. The economic and environmental aspects are therefore complementary. Greening of the economy reduces the environmental costs by the more efficient use of resources, while the new green technologies and techniques create jobs, give new impetus to the economy and strengthen the competitiveness of the European industry.

The European Commission promotes certain directions, through the Europe 2020 strategy, an EU growth strategy for the next decade. It focuses on the efficient use of exhaustible natural resources. The environmental policy can help achieving the overall objectives of the strategy of switching to a smart, sustainable and inclusive growth, which will turn Europe into a knowledge-based and resource-efficient economy.

The need to make effective use of the limited resources is an objective included in all *EU* policies. During the last decades, the *EU* has implemented a comprehensive policy to ensure water quality in Europe. It initially addressed health concerns. Actions have been taken to address the environmental impact of the main water-consuming sectors such as agriculture, industry and households.

The protection of water resources, freshwater and saltwater ecosystems, as well as domestic and drinking water has therefore become the basis of the European environmental protection system.

As a result, protecting the quality of Europe's water resources has become a top priority of the EU ever since it began to enact legislation in the field of environmental protection. The first directives, adopted before 1980s, set out a set of quality standards designed to protect human health and the environment, including surface waters, used to produce drinking water, domestic water, fish, shellfish waters, groundwater and water intended for human consumption. A directive of the same legislative "generation" has set standards for the discharge of substances into surface waters. However, the quality-based approach has proven to be insufficient to protect Europe's polluted waters. This was demonstrated in the late 1980s when eutrophication became a major problem in the North Sea, the Baltic Sea as well as in parts of the Mediterranean Sea.

As a result, the Urban Waste Water Treatment Directive (*UWWT*) requires Member States to invest in waste water collection and treatment infrastructure in urban areas, and the Nitrates Directive requires farmers to control the quantities of nitrogen fertilizer used on agricultural land.

The Integrated Pollution Prevention and Control (*IPPC*) directive, adopted a few years later, aims at minimizing pollutants discharged by large industrial plants [2].

All these policies and legislative acts were brought together in 2000, when the EU adopted the Water Framework Directive (*WFD*), favoring the institution of a global and unified approach to water legislation.

The Water Framework Directive establishes a legal framework to protect and restore water purity across Europe and to ensure its long-term and sustainable use (its official title is Directive 2000/60 / EC of the European Parliament and of the Council of Europe of 23 October 2000 establishing a framework for Community policy on water). The Directive establishes an innovative approach to water management based on river basins, geographical and hydrological natural units and sets deadlines for Member States to achieve ambitious environmental targets for aquatic ecosystems. The Directive deals with the subject matter of surface waters, transitional waters, coastal waters and groundwater [3].

In this general context, the PhD thesis "Strategies for Advanced Control of Biological Wastewater Treatment Processes", which aims at analyzing the performance of the biological treatment plant of wastewater and collected waters in the city of Galati, a medium-sized city, with a population of approximately 250,000-300,000.

The paper consists of five chapters which are presented below.

Chapter 1, with the title "The Current State in the Modelling and Automatic Management of Waste Water Treatment Processes", presents a review of the main current modelling and control issues encountered in the literature. In the operation of a wastewater treatment plant, the main objective is to efficiently eliminate pollutants from wastewater or to convert them into less harmful compounds, so that the effluent meets the discharge requirements by using the appropriate treatment technologies at the lowest possible costs. Lately, wastewater treatment plants tend to turn into resource recovery stations. Thus, wastewater is considered a resource from which nutrients, energy and water can be recovered. Mathematical models are very important in at least three current directions, which are of great interest, namely: training, design of treatment systems and process optimization. Over the years, various methods of wastewater treatment have been developed. The complexity, non-linearity and uncertainties of the wastewater treatment processes with active sludge have called for complex models that define the biological wastewater treatment processes as accurately as possible.

In the matter of automatic control of treatment plants, two important approaches distinguish themselves: one is decentralized control, which is oriented towards the control of the main interest rates in the process, and another is the control based on the mathematical model of the treatment process with the purpose of optimizing the operation of the whole plant.

Chapter 2, entitled "Presentation of the Wastewater Treatment Plant in Galati," describes the treatment plant, which contains one mechanical treatment phase, consisting of coarse and fine screens, and one desanding and grease separation system. The wastewater flow is directed to the primary clarifiers. At the output from the primary clarifiers, an intermediate pumping station is located, where the influent is directed towards the biological reactors. The biological treatment system performs the removal of organic components, nitrogen and phosphorus by means of oxygen injection, ferric chloride addition, and selected control strategies that promote biomass growth and sludge precipitation.

The SCADA architecture of the WWTP is presented, which was developed at a dispatching level in a client-server configuration with a redundant server. The communication between the plant PLCs is provided at the physical level via a redundant optical fiber ring. In order to retrieve information from the instrumentation equipment, Profibus industrial networks are used for each PLC.

The execution elements are controlled by PLCs by means of numeric output cards and Profinet and Profibus industrial network communication. This paper presents the main control loops as well as several screens from the SCADA application at the dispatcher level.

Chapter 3, called "Contributions to the Mathematical Modelling of a Wastewater Treatment Plant", presents the mathematical models for the activated sludge treatment processes that were used to model the treatment plant. Mathematical modelling was performed in the Simba simulation environment, compatible with Matlab-Simulink.

We used the mathematical models established in the literature, ASM1 (Activated Sludge Model No. 1), ASM2d (Activated Sludge Model No. 2d) and ADM1 (Anaerobic Digestion Model), as follows: Models of the ASM family for the effective modelling of the biological treatment process were used, to which the ADM model for modelling the anaerobic digestion process for sludge resulting from treatment was added; to define the influencer, the influent of the BSM-type models was used, characterized by variations of the variables in various modes but adapted to the case of the wastewater loads pertaining to the design data of Galati station.

The mathematical model of the treatment plant was determined gradually, beginning with the treatment of organic residues, nitrogen, nitrates, nitrites (by ASM1-type models) and continuing with sludge treatment (ADM1 model), then, in the third step, the phosphorus reduction took place (through ASM2d-type models). A detailed analysis of the technological performance of the treatment plant was carried out on the basis of specific indicators of these processes, similar to those used in benchmark-type models such as BSM1 and BSM2.

Chapter 4, with the title “Contributions to the Control of a Wastewater Treatment Station”, analyzes the control strategies of the WWTP in two cases, the first being the case where the system is developed using established ASM1 and ADM1-type models that aim at eliminating organic matter and nitrogen, and the second is the schematic of the station modelled with ASM2d for removing phosphorus loads.

The main control objectives were pursued in order to achieve a proper effluent quality such as control of dissolved oxygen in pools, regulation of recirculation flows (internal and external) and addition of ferric chloride to remove phosphorus. The purpose of control strategies was to achieve proper operation of the treatment plant with minimal costs and effluent quality not exceeding the legal limitations set.

To control the above-mentioned sizes, classical PI-type regulators were used, that can be easily implemented in specific control equipment such as programmable logic machines, which are very good in the current practice for automation of wastewater treatment plants. A comparative approach to several control strategies using the same control law was considered more useful than the use of various control techniques. This is because, at the entire system level, the quality parameters and indicators are mostly influenced by the selection of references and operating points in which the treatment processes take place.

One optimization method of the control loop references was analyzed in one of the strategies applicable to the treatment plant. Two optimization procedures were analyzed: one relaxation method in a simplified version and one stochastic method.

Chapter 5, entitled "Final Conclusions", presents the conclusions of this thesis, the original scientific contributions, as well as the future directions of research that result from the research in this thesis.

Chapter 1

1.1 Actual state in modeling and control of the wastewater treatment systems

1.2 Introduction

Water is a vital resource for humans with great importance for society. It is used in all industrial sectors, agriculture, transport, energy production, infrastructure, etc.

The Romanian legislation, currently in use, transposes the European Council Directives on wastewater treatment, including the European Directive no. 2000/60 / EC establishing a "legislative framework for a Community water policy"[3].

The problems of wastewater treatment and discharge in their natural receptors in Romania are subject to government decision HG. no. 188 of 28 February 2002 [5], supplemented by Decision no. 552/2005 and the decision no. 210/2007, which "approves technical standards for the collection, treatment and disposal of urban wastewater contained in NTPA-011 norm, wastewater discharge conditions in the local sewerage networks and wastewater treatment plants directly contained in NTPA-002/2002 norm and pollutant loading limits of industrial and municipal wastewater to discharge into the natural contained in NTPA-001/2002 norm".

Wastewater contains significant amounts of pollutants, resulting in the depletion of oxygen from water when it is discharged directly into surface water. The composition of waste water varies greatly depending on the areas where it is collected. Pollutants that contaminate water are generally solid or biodegradable or slowly biodegradable compounds, nutrients, toxic substances, pathogenic organisms, etc. Thus, a conventional wastewater treatment plant, as shown in Fig. 1.1, includes several multi-stage treatment processes. Each treatment stage is designed to remove a particular type of pollutant.

The main objective of wastewater treatment is to allow the discharge of urban wastewater into surface water, thus ensuring protection of the environment and human communities [6].

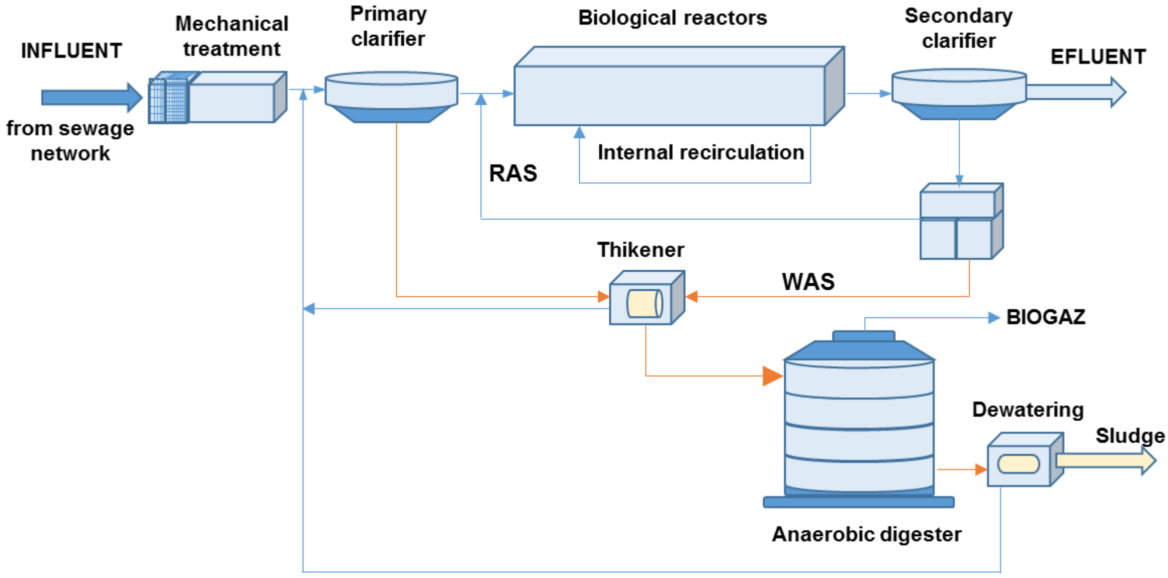


Fig. 1.1 - The general scheme of a wastewater treatment plant

The treatment scheme is chosen on the basis of comparative technical and economical calculations between several variants designed taking into account several factors, such as:

the availability of land available for the treatment plant that cannot have other economically useful uses, the existence of a sufficient space to achieve a sanitary protection area around the treatment plant, the obligation to fit within the legal limits of the concentration values with effluent loads after the purification process, the existence of an acceptor receptor (emissary) at an acceptable distance in which the treated waters are discharged , possibilities of storage, transportation or destruction of the sludge amounts resulting from the treatment processes and, last but not least, the possibility of providing a qualified treatment station.

In the operation of a wastewater treatment plant, the main function is to efficiently remove pollutants from wastewater or convert them into less harmful compounds so that the effluent meets the requirements of discharges using appropriate treatment technologies and the lowest possible costs. Cost savings can also be achieved by recovering some process resources, such as nutrients, biogas and water for re-use [7]. Due to the complex interactions of different variables related to the operation of the treatment, it is necessary to adopt advanced control strategies to maintain effluent concentrations below the legal minimum costs. In this sense, mathematical models and simulation tools for treatment processes have been found useful in predicting their behavior [8], [9] and exploring different approaches to improve the stations performance [10].

Mathematical models are very important fact mentioned in [11] and [12] have shown the three main areas of application: learning (training), treatment system design and process optimization.

As stated above, recently, wastewater treatment plants tend to turn into resource recovery stations. Currently, wastewater is considered as a resource where nutrients, energy and water can be recovered. Accordingly, the modeling of waste water treatment processes develops in the sense of adding new processes and state variables to existing mathematical models. For example, wastewater contains significant amounts of phosphorus, the concentration of which must be reduced to the legal limits to be discharged into surface waters because it favors the eutrophication process (a process by which water is enriched with nutrients - nitrogen and phosphorus) resulting in oxygen depletion of water and thus destroying their biological balance On the other hand, phosphorus is considered a limited resource that is estimated to be exhausted in a shorter period of 50-100 years [13], [14], or up to 300 years [15]. Thus, the recovery of phosphorus from wastewater becomes an important objective of the biological treatment process [16].

1.3 Actual state in the modeling of treatment systems

Over the years, various methods of wastewater treatment have been developed. An overview of the evolution of activated sludge processes can be found in [9]. The complexity, non-linearity and uncertainties of wastewater treatment processes with active sludge have imposed complex models that characterize biological wastewater treatment processes as accurately as possible. In 1983, the International Association on Water Quality (IAWQ), which became the International Water Association (IWA), formed a working group to develop and apply mathematical models of biological treatment systems in the design and operation of treatment plant. The two main objectives of the group were to review existing models and develop a simpler mathematical model that accurately approximates the behavior of the activated sludge treatment process, including carbon removal, nitrification and denitrification processes.

The first developed model, presented in 1987 in [22] was called Activated Sludge Model No. 1 (ASM1) and is the most widely used and accepted model for describing processes related to biological wastewater treatment, representing the basis for further development of ASM and their extension. These have been accepted by practitioners and researchers in the field of wastewater treatment over the past two decades. ASM models are presented in a tabular form containing a stoichiometric matrix and a kinetic vector [23], [24] using the notations recommended in [25].

The first activated sludge biological treatment model, ASM1, describes the biological carbon oxidation, nitrification and denitrification, and is therefore used to model the removal of carbon and nitrogen in active sludge treatment systems. Carbon and nitrogen compounds are subdivided into fractions based on biodegradability and solubility [12]. The model considers four processes: (1) the growth of autotrophic and heterotrophic bacteria, (2) their degradation, (3) the hydrolysis of organic particles, and (4) the ammonification of the soluble organic nitrogen. The reaction rate of each process is expressed as a series of smooth Monod type switching functions, corresponding to certain conditions (e.g., aerobic, anoxic, anaerobic process) [26].

Due to the need to meet the effluent quality standards for both nitrogen and phosphorus, the modeling of biological removal of phosphorus has become essential. This is a deficiency of the ASM1 model, which led to the development of a second model (ASM2) [27]. The ASM2 model is an extension of the ASM1 model and includes the biological and chemical removal of phosphorus in addition to carbon and nitrogen removal in the ASM1 model. In the ASM2 model three processes of hydrolysis of organic particles based on electron acceptors are noted. The fermentation process in the ASM2 model transforms the easily biodegradable substrate into fermentation products in the anaerobic medium. For phosphorus removal processes, the following variables: Inorganic phosphorus, phosphorus accumulation organisms (PAO), polyhydroxyalkanoates (PHA) and polyphosphates (PP) are included as additional state variables in the model. Other important processes included in the ASM2 model are phosphate precipitation with ferric hydroxide, $Fe(OH)_3$ and redissolving ferric phosphate formed, $FePO_4$.

After that, the ASM2 model was extended to the ASM2d model [28], by adding two new processes: (1) the storage of inorganic phosphorus as PP using the energy obtained by the anoxic respiration of PHA and (2) the anoxic growth of PAO. In both processes, the PP storage rate constant and the maximum rate of PAO growth are assumed to have low values under anoxic conditions, a phenomenon explained by the fact that only part of the PAO has denitrifying capacities or that denitrification occurs at a slower rate slow [28]. This model is widely used when analyzing improved biological phosphorus removal processes - *EBPR* (Enhanced Biological Phosphorus Removal) [29].

The ASM3 model [30] addresses some of the limitations of the ASM1 model. In the ASM3 model, it is considered that the substrate is first deposited in internal cell storage compounds before being taken up by heterotrophic biomass. Substrate storage, heterotrophic biomass growth, respiration of internal cell storage compounds and endogenous breathing are supposed to occur under aerobic and anoxic conditions.

Other significant extensions of the ASM models are ASM3-bioP and TUDP. ASM3-bioP includes phosphorus-PAO-accumulating organisms from ASM2d processes in ASM3 [31]. The phosphorus metabolism, which is included in ASM2 [32] and ASM2d [33], [34], was also included in the TUDP (Technical University Delft Phosphorus) model. These models have been extensively applied to treatment facilities.

It was necessary to develop alternative models of wastewater treatment (simplified) because ASM models were rather complex and quite difficult to use in automated control problems. Such a model is proposed in [39] and provides a comprehensive description of the wastewater treatment process. It has only four state variables (biomass, substrate, dissolved oxygen concentration, and recirculated sludge) which facilitates the testing of various classical or modern control structures.

Another simplified model is represented by "black box" models that may include, for example, neural networks. These models are, however, limited in describing all process dynamics, but can be used for subsystems or certain parts on-line control of the treatment plant. These types of models have been used in [40], [41].

Another direction of research of the IWA group is the development of benchmark models that include virtually all the wastewater treatment system. At the level of the association there is a working group on the "Benchmarking of Control Strategies for Wastewater Treatment Plant" which, together with the research group "European Cooperation in the Field of Scientific and Technical Research (COST) 624" propose the model "Benchmark

Simulation Model No.1" (BSM1) [42]. A more detailed description of BSM1 is provided in [43] and [44].

The Benchmark Simulation Model No. 2 (BSM2) represents a significant development of the BSM1 model at the treatment plant, taking into account both the water line and the sludge line. Thus, in addition to the BSM1 components, there are: a primary clarifier, a thickener, an anaerobic digester, a dewatering unit, and an exhaust water storage tank. The influent file for BSM2 is generated using an influent generator model shown in [48]. A more detailed description of BSM2 is presented in [47] and [44].

A development of the BSM2 which includes models of phosphorus removal processes is presented in more detail in [53] and [54].

1.4 Actual state in the control of treatment systems

The problem of automatic control of wastewater treatment plants there are two main approaches. A decentralized control approach that focuses on controlling the main process signals - control of dissolved oxygen, nitrogen or phosphorus. Another approach is a control based on a mathematical model of the process that aims to optimize the operation of the whole plant.

Decentralized control of the main process signals normally uses PI or PID classical regulators for control loops such as dissolved oxygen, nitrate concentration in a particular tank, or ammonium concentration at the outlet of the plant and / or phosphorus from the effluent.

Control based on the mathematical model of the treatment process resides in hierarchical control structures on several levels. At the lower level, we can use classical techniques such as classical PI, PID structures in which, for design, the nonlinear model is linearized around an operating point, or modern techniques such as multivariable linearity control or adaptive control, with a state estimator and parameter [39], [55], [56]. Using the same model robust [57], quantitative feedback theory [58], Gain Scheduling [59], or $H\infty$ [60], predictive [61] or intelligent [62] techniques have been implemented. Using the ASM1 model, a three-level hierarchical structure is proposed in [63]. Another approach that is used in control of the treatment process is given by control based on artificial intelligence techniques. The knowledge gained by operators is used, such as expert systems, fuzzy, neurofuzzy [64], [65]. Also, data-driven techniques, such as Virtual Reference Feedback Tuning, have been proposed in [66].

Chapter 2

Presentation of the wastewater treatment plant from Galati

2.1 Introduction

The main objective approached in the doctoral thesis consisted of mathematical modeling and control of the Galati city wastewater treatment plant, recently modernized plant, containing all the treatment stages, together with the specific equipment. The treatment plant is dimensioned for a population of approximately 300,000 inhabitants and treats domestic waters containing organic waste, nitrite, nitrate, phosphorus, etc.

2.2 General structure of wastewater treatment plant

The wastewater treatment plant in Galati includes three stages of treatment as follows (Fig. 2.1):

1. Mechanical treatment stage
2. Biological treatment stage
3. Sludge treatment

Fig. 2.1 – Overview of the Galati Wastewater Treatment Plant [75]

The problem of wastewater treatment plant sludge is an important one at the moment, which generates increasing costs for the local community. This is because there are inconsistencies in legislation that make it impossible to leverage the sludge.

Chapter 3

Contributions to the mathematical modeling of a wastewater treatment plant

3.1 Introduction

The mathematical modeling of the wastewater treatment plant in Galati, was developed using "State of Arts" models from the literature, such as ASM (Activated Sludge Model), ADM (Anaerobic Digestion Model), BSM (Benchmark Simulation Model), was implemented in the SIMBA environment , as follows: type ASM models for modeling biological treatment, to which was added ADM model for modeling of anaerobic digestion for sludge and BSM model type for defining the influent adapted to the wastewater charges of Galati.

The mathematical model of the plant was determined gradually, starting with the treatment of organic matter, nitrogen, nitrates, nitrites (by-type patterns ASM1) and continuing with the treatment of the sludge (sample ADM1) and then, in the third step, has been reduced phosphorus (by ASM2d models). Chapter 3 also contains a detailed analysis of the technological performance of the treatment plant based on specific process-specific indicators for a city with a population of 250,000 to 300,000 inhabitants, such as Galati.

3.2 Selection of treatment station influent (case of Asm1 and Adm1 models)

The design of the influent for the treatment plant is very important because it represents the main disturbance of the biological treatment process by its loading with residues. Obviously, these disturbances must be rejected by appropriate control laws so that an effluent is obtained at the outlet of the treatment plant that complies with the legislation on wastewater quality and environmental protection. For the wastewater treatment plant in Galati, an influent was chosen from the one defined in the BSM1 benchmark, which was dimensioned to the specific waste loads in Galati. For this purpose, three types of influent were defined, corresponding to the following meteorological conditions: "dry weather", "rainy weather", "and storm weather". These regimens are concretized into three data sets defined in three files containing values of the influent variable concentrations over a 14-day period, sampled at 15 minute. These data are representative of their use in control schemes of a treatment plant. The three files present the daily, day and night variations of input flow and organic components. Specific weekly variation of the data were also included. Thus, in the weekend end, the flow peaks are lower than the other days of the week, which is actually a normal load for a biological treatment plant.

3.2.1 The "dry weather" regime

The first file contains a characteristic data set for the "dry weather" regime and describes normal daily diurnal flow and organic load (COD) variations. Thus, the maximum flow increase is 1.74 times higher than the average flow rate over the 14-day period considered.

3.2.2 The "rain weather" regime

The second file contains a characteristic data set for a period of rain. The influent flow during this rainfall reaches a level almost twice as high as during the dry period, which is increased for a longer period of time, over two days.

3.2.3 The "storm weather" regime

The third file contains a characteristic set of data for a dry period of time, with the inclusion of two storm events. The first storm event has a high intensity and a short duration, the second one has the same intensity but a slightly longer duration.

During the first event of this period, the sewer network is "washed", which leads to a significant increase in particulate matter that is directed to the treatment plant. This is found in the data files by a significant increase in concentrations of suspended particulate matter inert matter.

For the dry weather regime, the increase in organic matter load is 2.34 times higher than the average over the same period. For the rainy weather regime, there is no significant variation in organic matter load compared to the dry weather regime. Organic loading decreases by 7.6% for COD and by 6.89% for BOD5.

During the first storm event, it removes particles from the sewage network and there is an increase in the concentration of organic substances and suspended solids, but of very short duration. During the second event there is a moderate decrease in the organic matter load - COD. This result is also visible for nitrogen and its components (a moderate decrease in the total nitrogen of the influent).

3.3 Evaluation of treatment processes performances

Limits of pollutant loads for discharged waters from urban treatment stations are set by law. In Romania, these limits are set by *NTPA* – 011 norm [5]. It is specified in the legislation that prior to evacuation to natural receptacles urban waste water must be subjected to biological treatment processes in order to limit the concentrations of biological substances, suspended matter, total nitrogen and phosphorus in the spilled effluent Another act normative, approved by Order no. 163 of 14 April 2005, Part IV, Indicative, NP 107-04, contains prescriptions and data necessary for the design of water-based constructions and installations where advanced sewage treatment processes are carried out. Also here are the calculation methods for nitrogen and phosphorus in the wastewater components from which the total nitrogen and the total phosphorus from the effluent of the treatment plant are obtained.

Total nitrogen is the nitrogen of the nitrogen compounds in the waste water and consists of organic nitrogen to which is added the inorganic nitrogen. Organic nitrogen is nitrogen in biomass. Inorganic nitrogen consists of ammonium nitrogen, NH_4–N, nitrate nitrogen, NO_3-N, and nitrite nitrogen, NO_2-N. When we know the values of the above componentsNH_4^+,NO_3^-,NO_2^-, these being measured or estimated with mathematical model, the amount of nitrogen in each component will be calculated as follows:

$$N_{tot} = NH_4^+ - N + N_{organic} + NO_3^- - N + NO_2^- - N \tag{3.28}$$

$$NH_4^+ - N = 0.777 \cdot NH_4^+ \text{ [mg/l]} \tag{3.29}$$

$$NO_3^- - N = 0.226 \cdot NO_3^- \text{ [mg/l]} \tag{3.30}$$

$$NO_2^- - N = 0.304 \cdot NO_2^- \text{ [mg/l]} \tag{3.31}$$

In the calculations of the parameters $N_{tot}, NH_4^+ - N$, $NO_3^- - N$ of the effluent, for the overflow analysis the values of the coefficients in equations (3.28) – (3.31) were used.

Total phosphorus is composed of organic phosphorus and mineral or inorganic phosphorus. Mineral phosphorus is composed of phosphate and polyphosphates. Having the phosphate and / or polyphosphate values from laboratory analysis or mathematical model equations, the total phosphorus value will be calculated as follows:

$$P_{tot} = PO_4^- - P + Polifostat - P + P_{organic} \tag{3.32}$$

$$PO_4^- - P = 0.326 \cdot PO_4^- \text{ [mg/l]} \tag{3.33}$$

As in the previous situation, the coefficients in equations (3.32) – (3.33) were used in the calculations of the parameters $P_{tot},\ PO_4^- - P$ of the effluent for the overflow analysis.

The assessment of the performance of the control strategy applied to the performance of the treatment plant consists in the evaluation of some quality and cost indicators based on influent, effluent and sludge parameters. These indicators are: 1. the effluent quality, 2. the quality of the influent, 3. the operating cost, and 4. the total cost index [43], [47].

3.4 Modeling the wastewater treatment plant considering the anaerobic digestion part (ASM1 and ADM1 models)

The Galati wastewater treatment plant includes four secondary clarifier and two anaerobic digesters. In this section, one of the four biological treatment lines, with a primary clarifier and a digester for anaerobic fermentation of the sludge, is considered for analysis.

3.4.1 Mathematical model implementation in SIMBA simulation environment

Primary clarifiers produce a quantity of sludge that is transferred directly into the anaerobic digester. The amount extracted daily is about 200 m^3 for all four units. Thus, for a single treatment line, it was considered that the extracted sludge flow is based on the flow rate of the influent entering the treatment plant, but limited to 50 m^3/day.

3.4.2 Analysis of input, output and measurable process parameters

From a systemic perspective, the biological process of wastewater treatment and fermentation of sludge can be represented as follows: (Fig. 3.55):

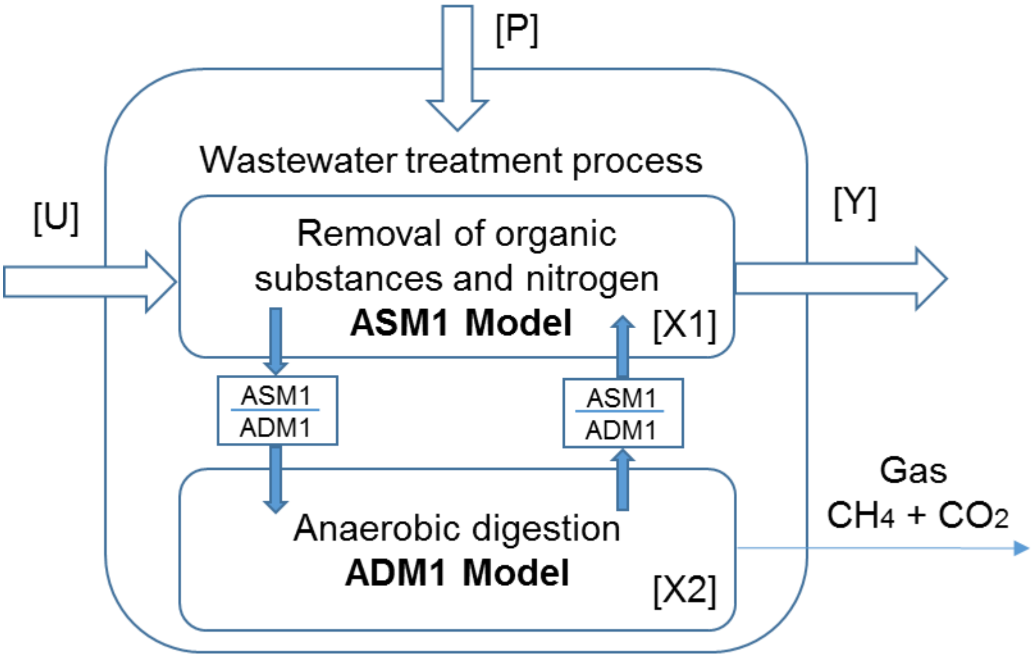


Fig. 3.55 - The model of the wastewater treatment process containing the anaerobic digester (ASM1 coupled with ADM1)

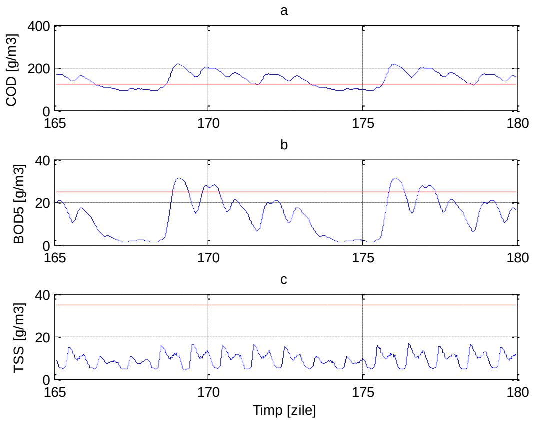
3.4.3 Simulation result – model ASM1 + ADM1

The model of the wastewater treatment plant, which includes the anaerobic digester, was simulated in all three regimes considered, the dry weather regime, the rainy weather regime, and the storm weather regime. Influent is as described in section 3.2, also used in previous simulations, following the limits for effluent concentrations (traced red in the following figures).

The simulations were conducted in open loop with constant values for the oxygen insufflated in the aerated tanks, for the external and internal circulation flows - and for the excess sludge flow. Two operating points were considered.

The simulation was performed for a period of 180 days, and the concentrations for organic charges, suspended solids and nitrogen were calculated over the last 14 days of the simulation period.

- Point A of operation - The case of dry weather (Fig. 3.56 – 3.58)



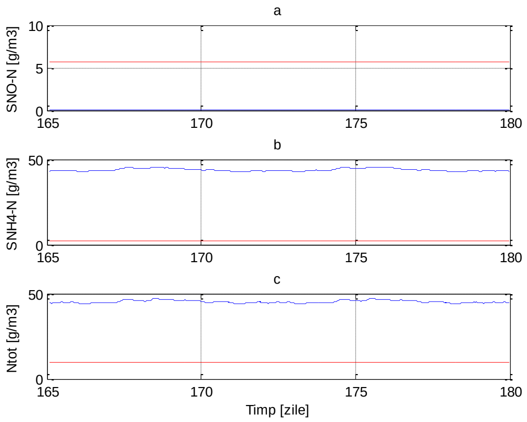


Fig. 3.56 - Biological loads of the effluent at point A of operation, "dry weather"

Fig. 3.57 - Nitrogen loads of the effluent at point A of operation, "dry weather"

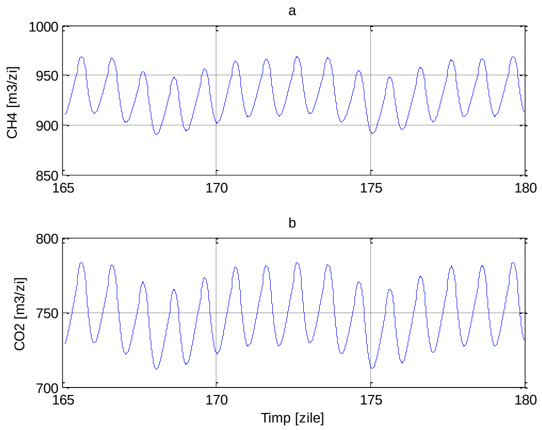
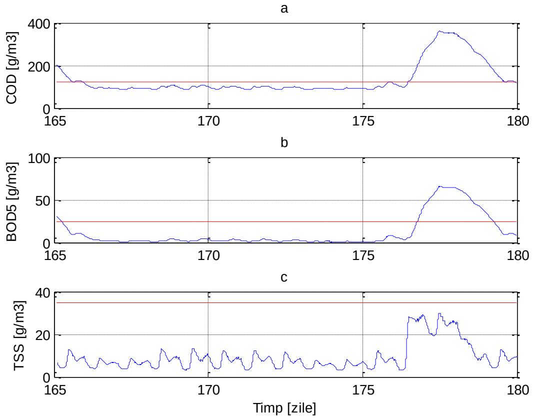


Fig. 3.58 - Gas production at point A of operation, "dry weather"

- Point A of operation - The case of rainy weather (Fig. 3.59 – 3.61)



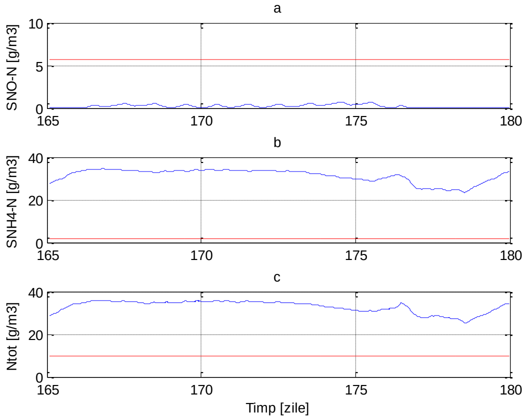


Fig. 3.59 - Biological loads of the effluent at point A of operation, "rainy weather"

Fig. 3.60 - Nitrogen loads of the effluent at operating point A, "rainy weather"

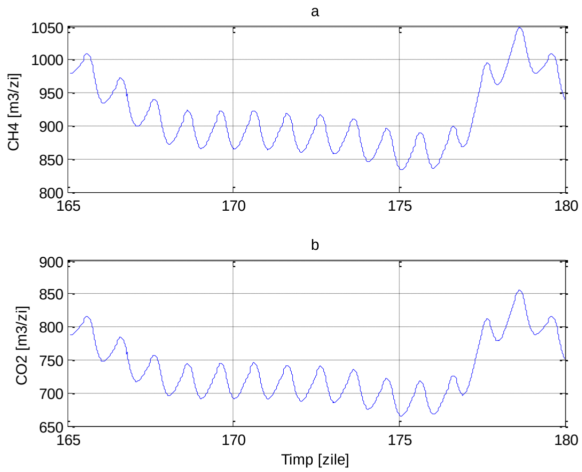


Fig. 3.61 - Gas production at operating point A, "rainy weather"

- Point A of operation - The case of the weather regime with storm (Fig. 3.62 – 3.64)

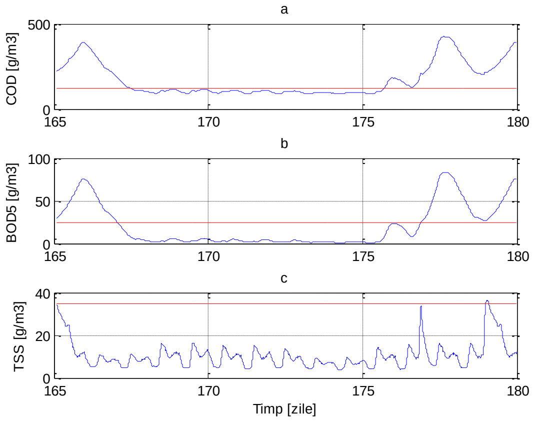


Fig. 3.62 - Biological loads of the effluent at operating point A, "storm weather"

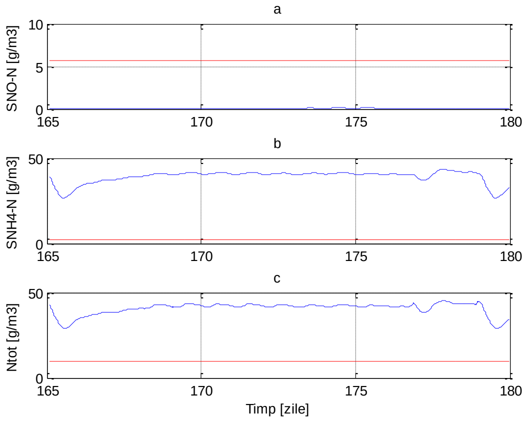


Fig. 3.63 - Nitrogen loads of the effluent at operating point A, "storm weather"

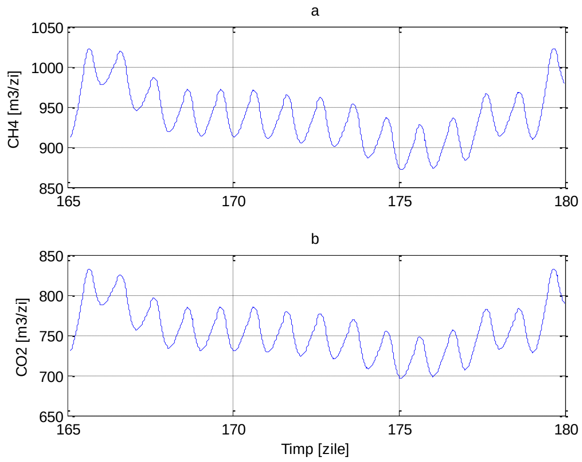
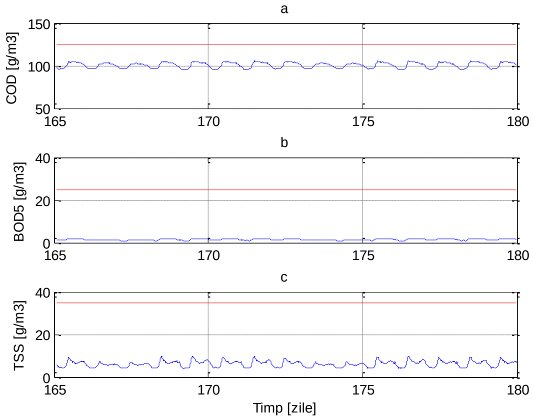


Fig. 3.64 - Gas production at operating point A, "storm weather"

- Point B of operation - The case of the dry weather regime (Fig. 3.65 – 3.67)



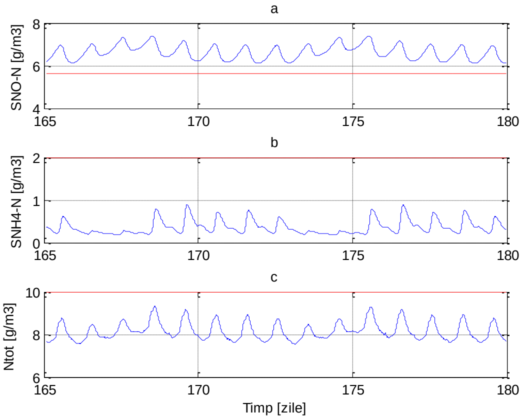


Fig. 3.65 - Biological loads of the effluent at point B of operation, "dry weather"

Fig. 3.66 - Nitrogen loads of the effluent at operating point B, "dry weather"

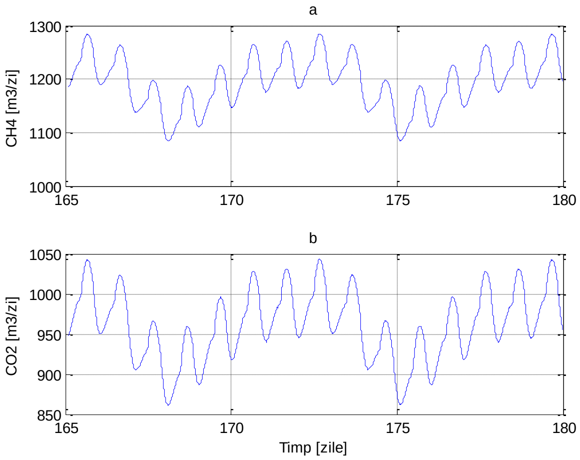
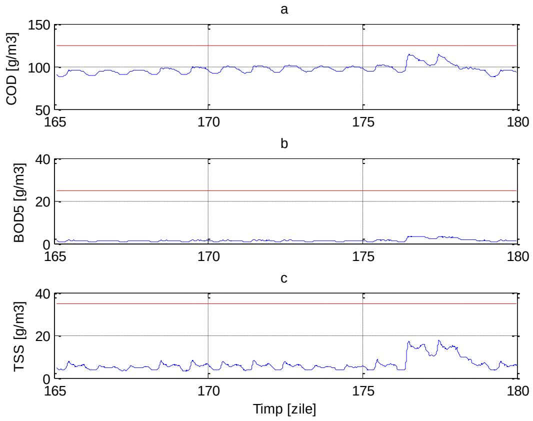


Fig. 3.67 - Gas production at operating point B, "dry weather"

- Point B of operation - The case of rainy weather (Fig. 3.68 – 3.70)



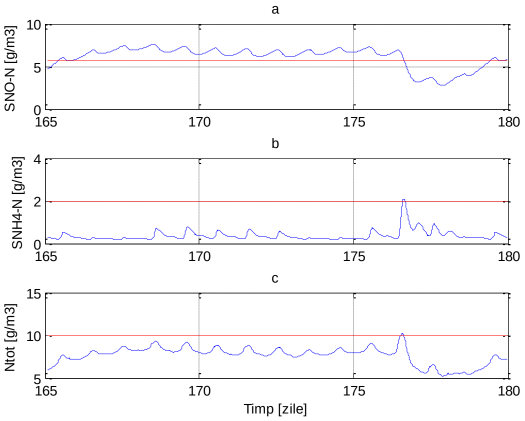


Fig. 3.1 - Biological loads of the effluent at point B of operation, "rainy weather"

Fig. 3.69 - Nitrogen loads of the effluent at operating point B, "rainy weather"

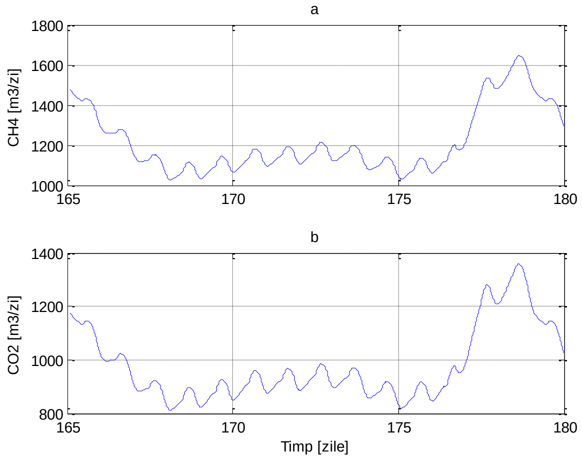


Fig. 3.70 - Gas production at operating point B, "rainy weather"

- <u>Point B Operation - The case of the weather regime with a storm (Fig. 3.71 – 3.73)</u>

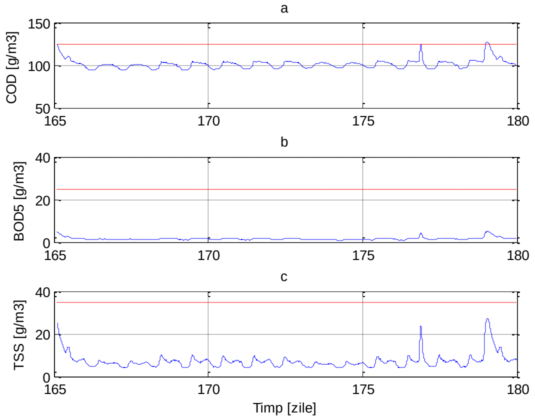


Fig. 3.2 - Biological loads of the effluent at operating point B, "storm weather"

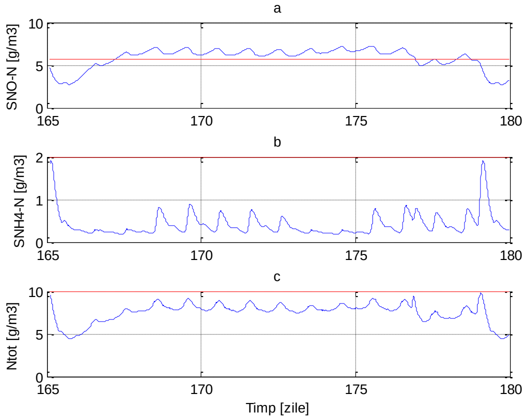


Fig. 3.72 - Nitrogen charges of the effluent at operating point B, "weather with storm"

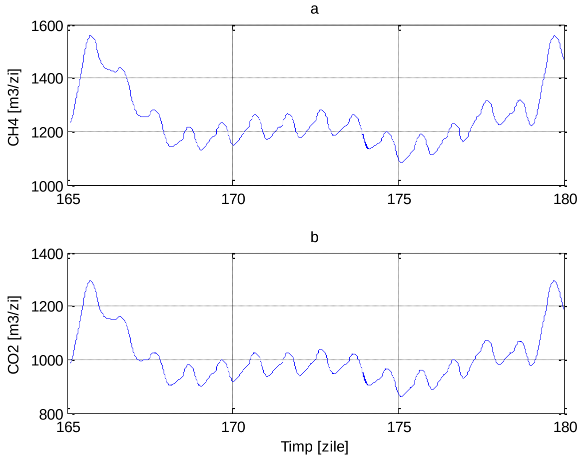


Fig. 3.73 - Gas production at operating point B, "storm weather"

Analyzing the results obtained by simulating the operation of the treatment plant in A and B points for the case of the elimination of organic substances, nitrogen and its components, plus the part of the anaerobic digester and the calculation of the indicators at the two points operation, it results that: in operating point B the effluent quality is significantly better than the operating point A (EQ is lower in B), but with an approximate cost of 2.5 times, due to higher energy consumption.

3.5 Modeling the wastewater treatment plant including and phosphorus elimination (ASM2d model)

In this case, the Simulink scheme includes the ASM2d model derived from the ASM1 model for the removal of organic substances (carbon, nitrogen and their components) to which the model part corresponding to phosphorus removal is added. Phosphorus removal is done by the addition of ferric chloride. The structure of the station is similar to that in [84] but the influent is obtained based on the design concentration values of the station..

3.5.1 Analysis of input, output and measurable process parameters

The systemic representation of the wastewater treatment process including phosphorus removal is given in Fig. 3.75:

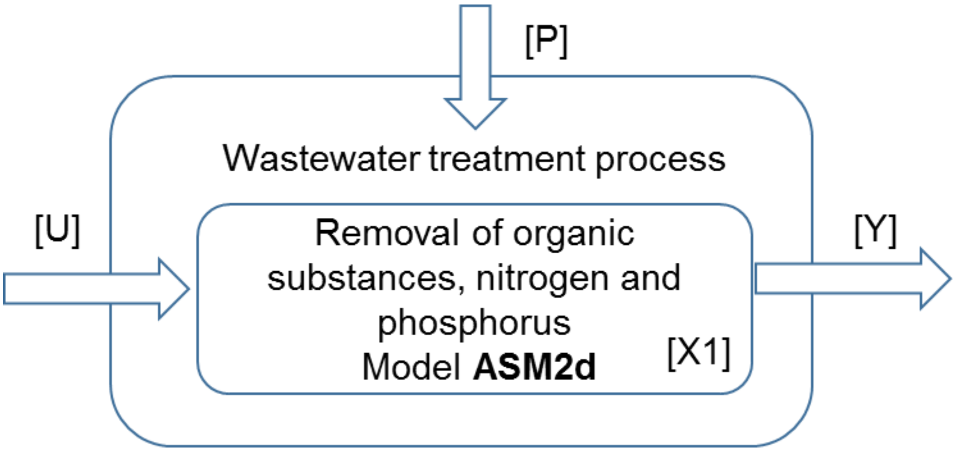


Fig. 3.75 - The systemic scheme of the wastewater treatment process including phosphorus removal (ASM2d)

3.5.2 Simulation result - model ASM2d

- Point A of operation, dry weather - ASM2d (Fig. 3.76 – 3.78)

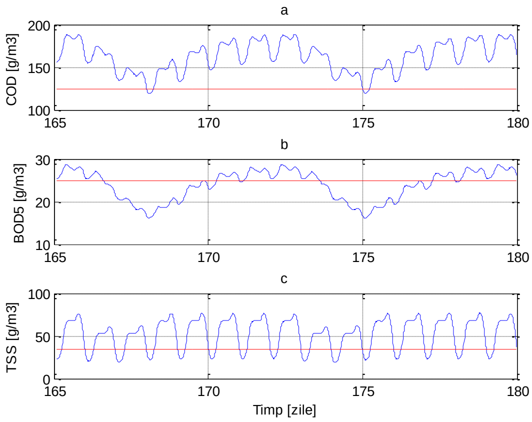


Fig. 3.76 - Biological loads of the effluent at point A of operation, "dry weather"

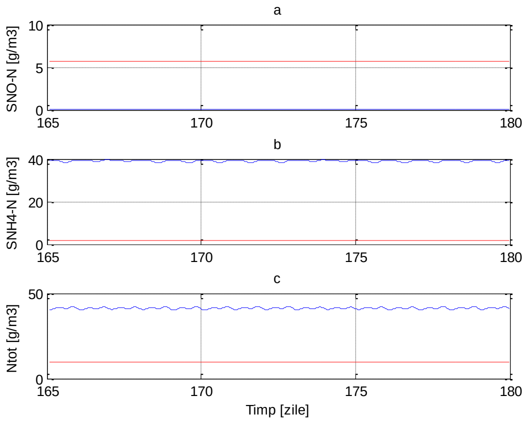


Fig. 3.77 - Nitrogen loads of the effluent at point A of operation, "dry weather"

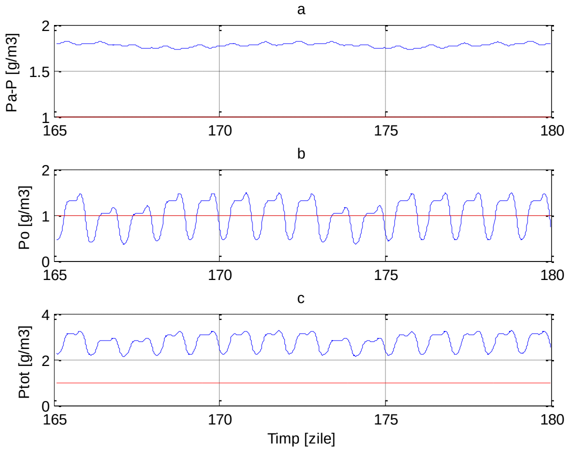
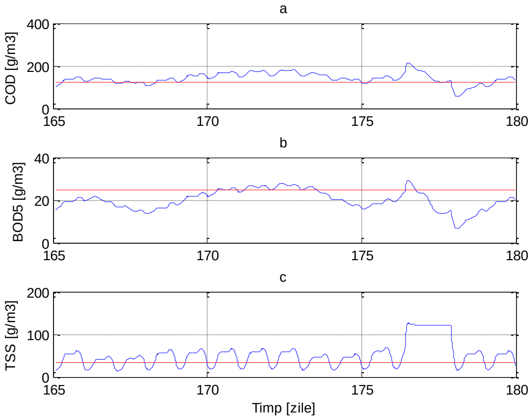


Fig. 3.78 - Phosphorus loads of the effluent at point A of operation, "dry weather"

- Point A operating, rainy weather - ASM2d (Fig. 3.79 – 3.81)



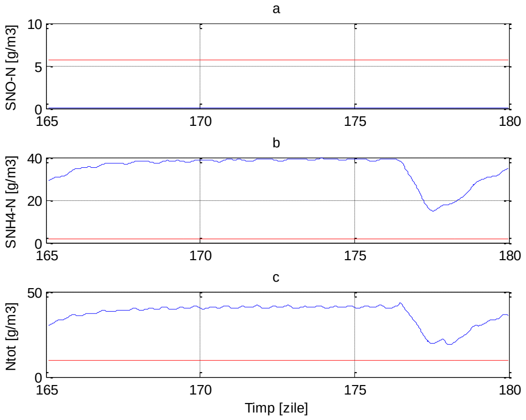


Fig. 3.79 - Biological loads of the effluent at point A of operation, "rainy weather"

Fig. 3.80 - Nitrogen loads of the effluent at operating point A, "rainy weather"

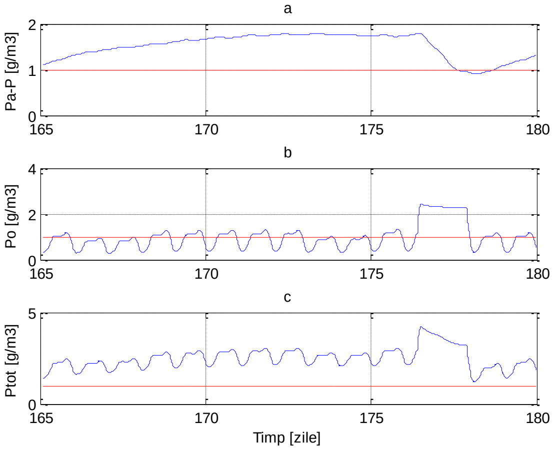
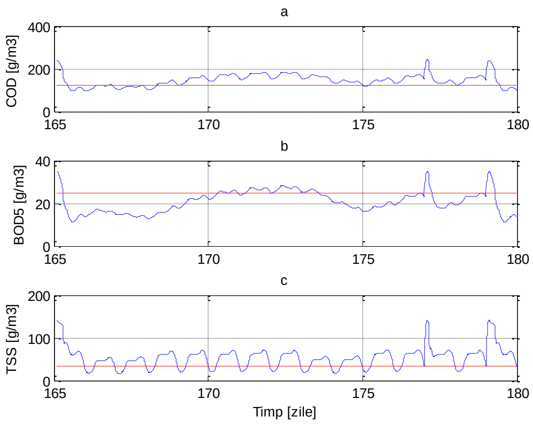


Fig. 3.81 - Phosphorus loads of the effluent at point A of operation, "rainy weather"

- Point A operating, storm weather mode - ASM2d (Fig. 3.82 – 3.84)



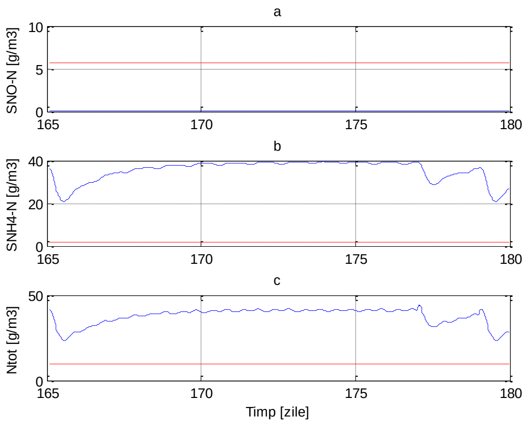


Fig. 3.82 - Biological loads of the effluent at operating point A, "storm weather"

Fig. 3.83 - Nitrogen loads of the effluent at operating point A, "storm weather"

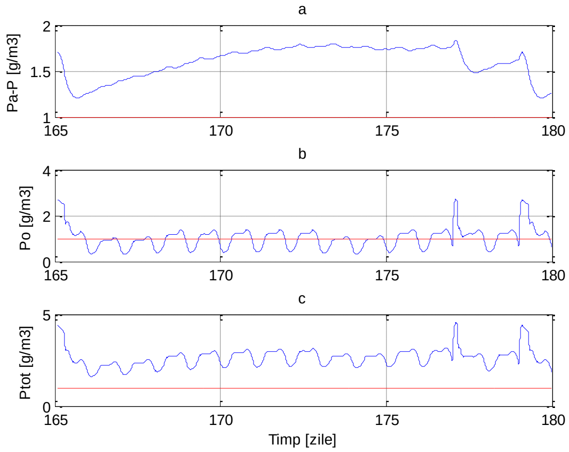
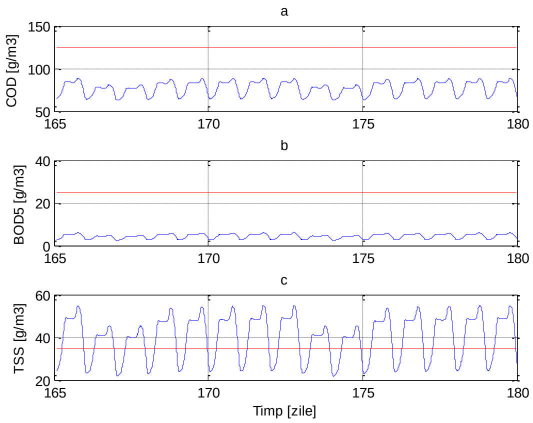


Fig. 3.84 - Phosphorus loads of effluent at operating point A, "weather with storm"

- Point B of operation, dry weather - ASM2d (Fig. 3.85 – 3.87)



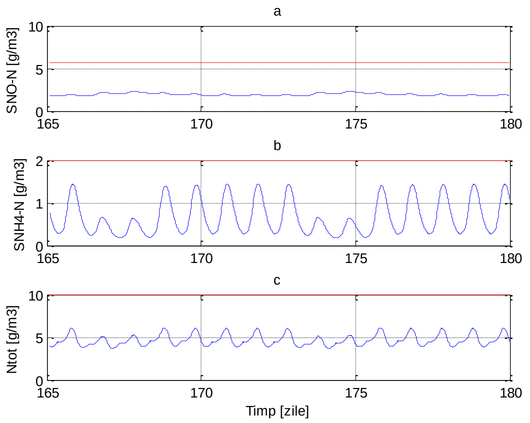


Fig. 3.85 - Biological loads of the effluent at point B of operation, "dry weather"

Fig. 3.86 - Nitrogen loads of the effluent at operating point B, "dry weather"

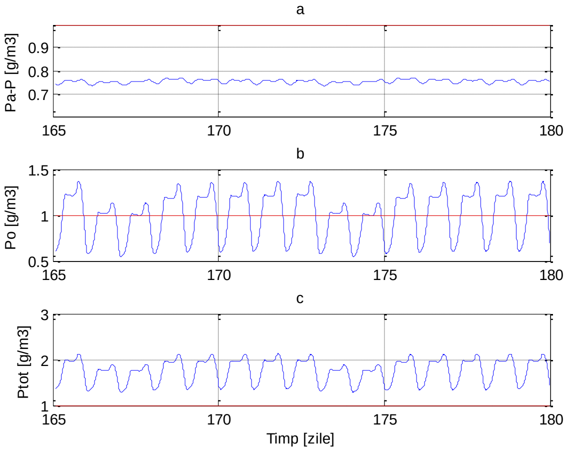


Fig. 3.87 - Phosphorus loads of the effluent at operating point B, "dry weather"

- Point B operating, rainy weather - ASM2d (Fig. 3.88 – 3.90)

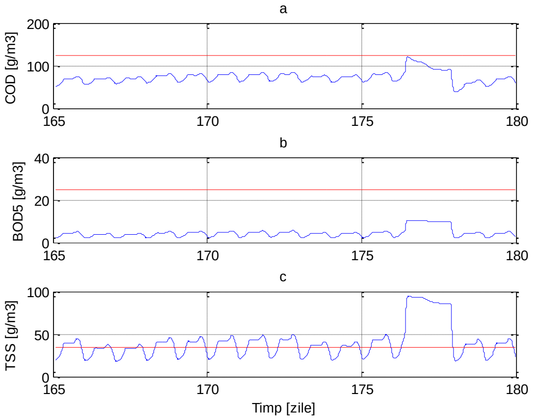


Fig. 3.88 - Biological loads of the effluent at point B of operation, "rainy weather"

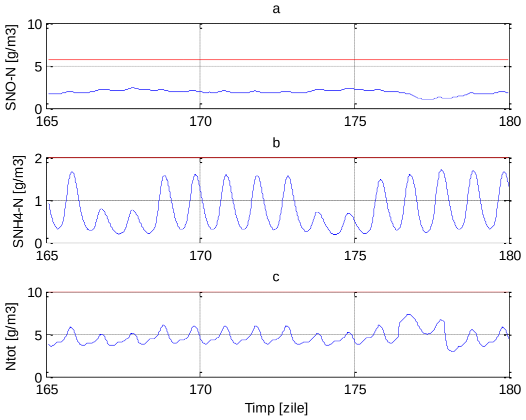


Fig. 3.89 - Nitrogen loads of the effluent at operating point B, "rainy weather"

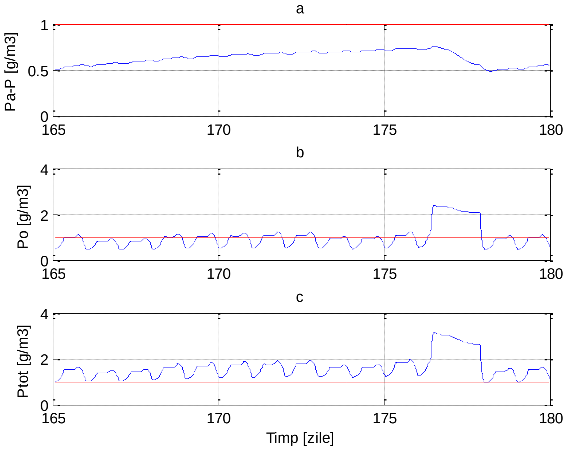


Fig. 3.90 - Phosphorus loads of effluent at operating point B, "rainy weather"

- <u>Point B operating, storm weather mode - ASM2d </u>(Fig. 3.91 – 3.93)

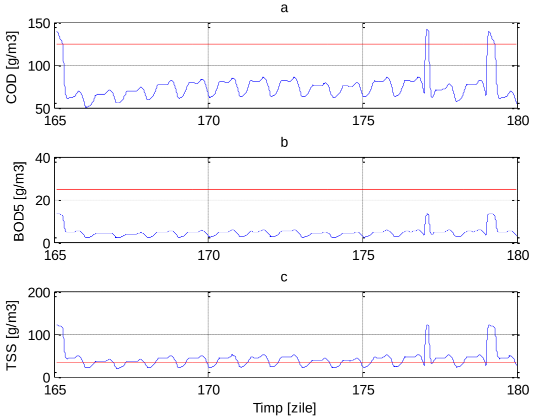


Fig. 3.91 - Biological loads of the effluent at operating point B, "storm weather"

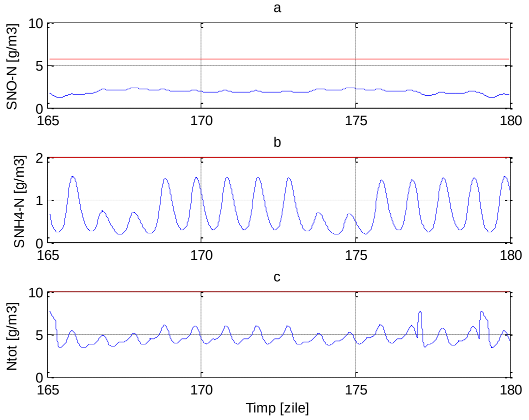


Fig. 3.92 - Nitrogen charges of the effluent at operating point B, "weather with storm"

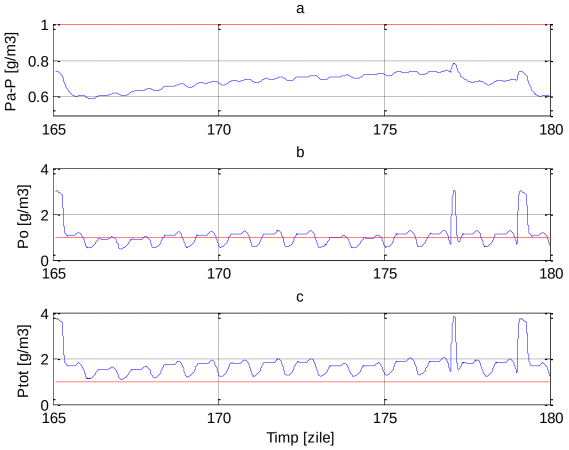


Fig. 3.93 - Phosphorus loads of the effluent at operating point B, "storm weather"

Analysis of the results obtained by wastewater plant simulation with ASM2 model, at the operation points A and B for the case of the elimination of organic substances, nitrogen and phosphorus in the waste water, as well as indicators calculation at the two mentioned operating points, show the following:

- From Fig. 3.76 - 3.84 (operating point A) results in very high exceedances at all the important quality parameters of the effluent of the treatment plant (*COD, BOD*$_5$, *TSS, *T_{khj}, N_{tot}, and P_{tot}).
- From Fig. 3.85 – 3.93 (operating point B results exceeded for two of the main quality parameters (*TSS* and P_{tot}) in all three operating modes. In this case, P_{tot} permanently exceeds the limit in all operating modes.

Chapter 4

Contributions to the control of a wastewater treatment plant

4.1 Introduction

In Chapter 3 of this doctoral thesis (Contributions to the Modeling of the Wastewater Treatment Process), were used as input data the concentration and flows that considered as the design basis for the wastewater treatment plant in Galati. The conclusions of the simulations in Chapter 3 show that the treatment plant has certain limitations in operation if the actual loads are the maximum for which it was designed, especially on the phosphorus removal side. The analysis from [69] where authors use different reference for times in week working days and weekends has shown that no significant improvement in performance indicators is achieved. A comparative approach to several control strategies using the same fixed reference for the control loop throughout the simulation period was considered more useful than the control techniques comparison. This is because, at the system level, the parameters and quality indicators are mostly influenced by the choice of the references and the operating points where the treatment processes take place.

4.2 The real influent of the wastewater treatment plant for ASM1 and ADM1 models

For an accurate evaluation of the control strategies of the treatment plant, we used an influent with a composition as close as possible to the one measured in Galati that is currently (in 2017) processed by the wastewater treatment plant. In order to evaluate the control strategies, we generate a data file characteristic of all three regimes as follows: the first two weeks are dry weather, the next two weeks are related to the rainy weather regime, there is a new regime of dry weather, the next two weeks correspond to the storm weather regime, and for the last two weeks of the series, a dry weather period is again selected. In this way, there is a data file of components of the influent that lasts for a period of 70 days in which two perturbations occur due to the meteorological events considered, an event corresponding to the rainy weather and the storm weather. To achieve the most accurate results, three such influent data files were concatenated in the simulations, resulting in a data file of approximately seven months (210 days) with six rainy weather events and storm weather.

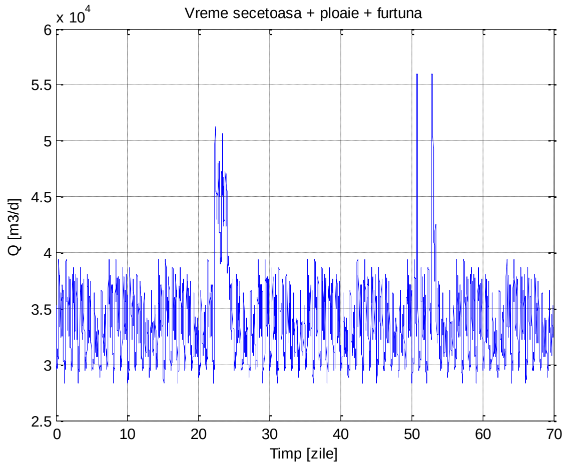


Fig. 4.10 - Variation of the combined influent flow rate

4.3 The control strategies of the WWTP for reducing of organic and nitrogen substance

The Wastewater Treatment Plant of Galati is modeled in SIMBA simulation environment using ASM1 type models for biological reactors (tanks $B_1 - B_7$) and ADM1 model for anaerobic digester. The station model is similar to the one presented in section 3.4. It includes as primary elements a primary clarifier, a biological treatment line consisting of seven basins, the secondary clarifier and the anaerobic digester preceded by a sludge thickening system. A simplified scheme of the treatment station is shown in Fig. 4.21.

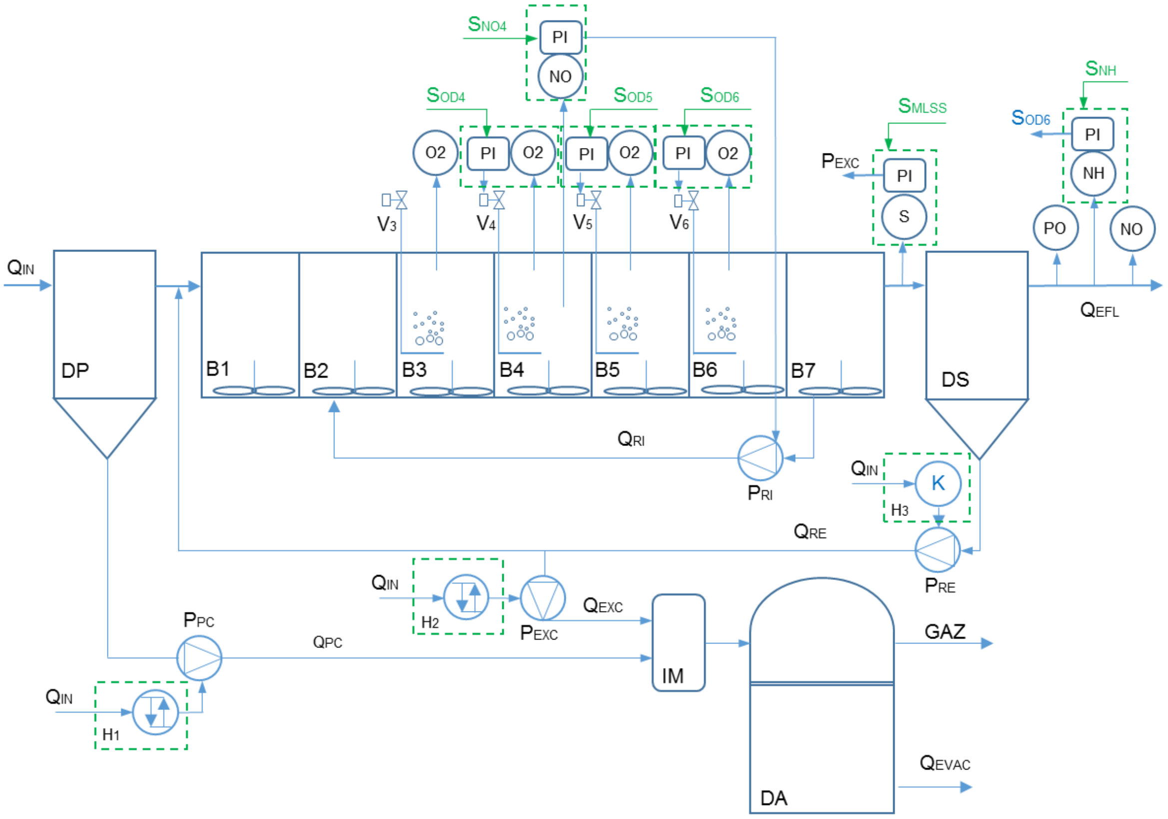


Fig. 4.21 - Simplified scheme for the treatment plant - ASM1 + ADM1

For the evaluation of the control strategies, was used an aggregate influent, consisting of the alternation of periods of dry weather, rainy weather and storm weather, as presented in section 4.3, for a total period of 210 days. Functional analysis, indicators calculation and the exceedances was elaborate during the last 70 days of the 210 days of the simulation.

Were considered five control strategies that use regulators classical PI for the control loops (used to adjust the concentrations of dissolved oxygen, the nitrate through the internal recirculation, the solid matter in suspension by the flow of sludge in excess, adjustment of ammonia in the effluent by the reference oxygen dissolved in basin B_6). It includes an anti-windup sequence for the control system, used to limit the effect of integration component of the regulator when operating technological limitations are imposed to the actuators. Controller's parameters are similar to those used in BSM2 but adjusted to the command value and the scheme used for simulation.

The five control strategies considered in the paper determine five different points of operation for the treatment plant, allowing the choice of the strategy that assure a minimum exceeding number for effluent limits, minimal operating costs and finally a very good effluent quality. Effluent parameters, operating costs and its quality indicators are calculated according to the relations of Section 3.5.

The five strategies considered are the following:

Strategy S_1 – The process runs in open loop

Within this control strategy, the B_4, B_5 and B_6 basins are considered to be aerated, the B_2 and B_3 basins are anoxic and the B_1 - anaerobic basin. The following sub-systems are also in operation: internal recirculation, external recirculation, excess sludge extraction, and sludge extraction from the primary clarifier. In this situation, the execution elements are commanded at the maximum operating value from the design data of the treatment station, without adjustment. The operating point B means an open loop operation point with all the execution elements commanded to the maximum values in the design specification of the treatment station. For strategy S_1, in Fig. 4.22 – 4.24 shows the evolution of effluent parameters and the production of methane gas in the anaerobic digester for the last 70 days analyzed.

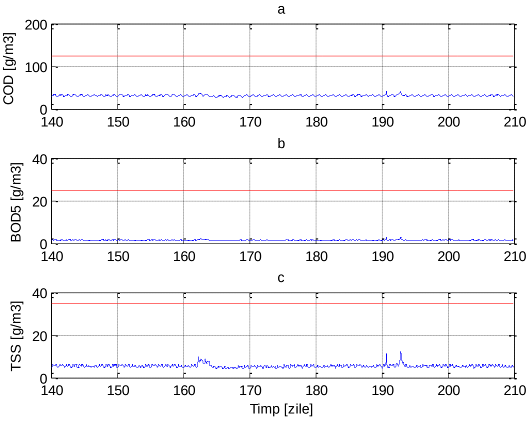


Fig. 4.22 - Variations in organic loads in strategy S_1

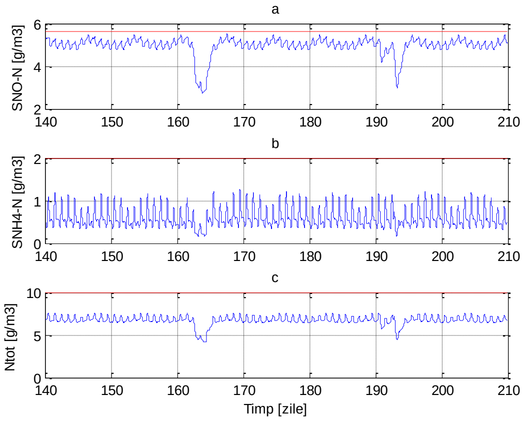


Fig. 4.23 - Nitrogen load variations for strategy S_1

The values of organic charges, *COD* and BOD_5, as well as the concentration of suspended solids, *TSS*, re below the legal limit. Disturbances inflow due to rain and storm events are rejected, variations in size due to these disturbances are almost nonexistent. Total nitrogen is within acceptable limits, there is a decrease in rainfall and storm events. The ammoniacal nitrogen concentration is below the maximum allowed, the average is just below the legal limit, and the nitrate concentration falls within limits, the variations reaching here very close to the limit. During rainfall, a more pronounced decrease occurs for nitrate nitrogen and for total nitrogen, for ammoniacal nitrogen variations are not significant.

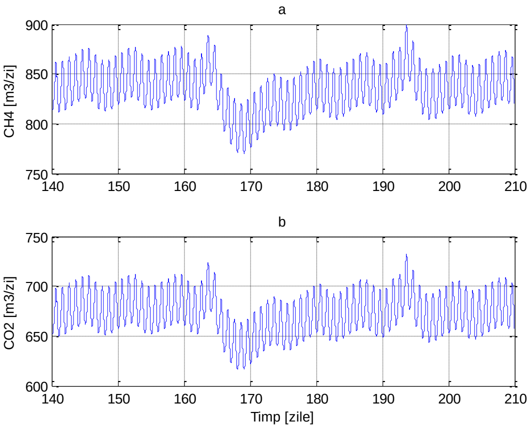


Fig. 4.24 – Production of CH_4 and CO_2 in the anaerobic digester in case of strategy S_1

Strategy S_2 – Control of dissolved O_2 concentration in B_5 and B_6 basins and concentration of nitrates in basin B_4 through internal recirculation

Within this control strategy, basin B_1 is anaerobic and the basins B_2 and B_3 are anoxic. The content of these three basins is continuously mixed through the mixers. Basin B_4 is configured anoxic and is continuously mixed. Basins B_5 and B_6 are aerated, the dissolved oxygen references for each being set to 4 mg/l. The outputs of the dissolved oxygen regulators represent the command for the regulating valves on the blower air circuit. In B_4 basins the nitrate concentration is controlled by internal recirculation. The nitrate reference (NO_3) is set to 1 mg/l. The output of the internal recirculation regulator is the command for the pump on the internal recirculation circuit. Excess sludge is extracted based on the input flow value. Thus, if the flow rate exceeds 40000 m^3 hen the sludge flow ratio extracted from the excess sludge pumps is 720 m^3 of sludge. If the input flow drops below 38500 m^3, then the reference is 360 m^3. The sludge in the primary clarifier is extracted according to the same rule as the excess sludge. For an inlet flow exceeding 40000 m^3, an extraction flow of 250 m^3 will be imposed on the pumps, and if the flow is below 38500 m^3, the reference will be 60 m^3 of extracted sludge.

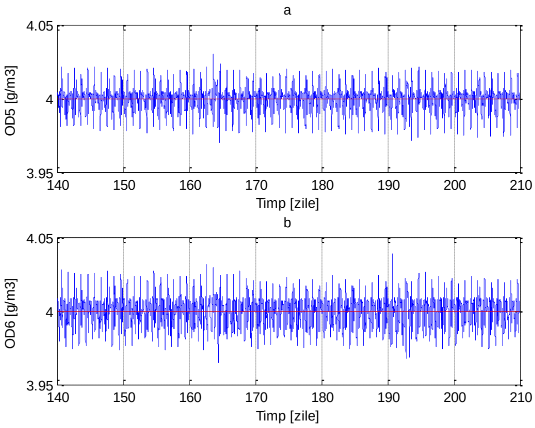


Fig. 4.26 - Adjustment of dissolved O_2 concentration in B_5 and B_6 basins

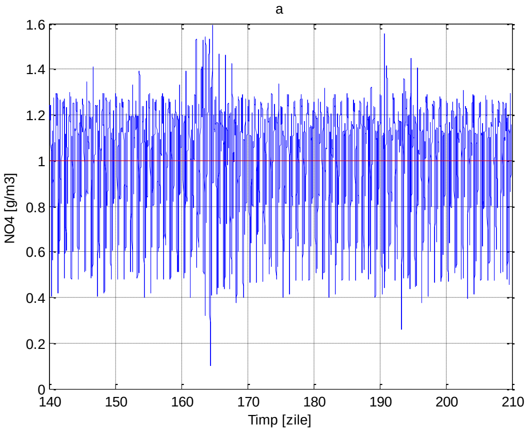


Fig. 4.27 - Adjustment of nitrate concentration in basin B_4

For the last 70 analyzed days, the variations of the effluent parameters and the production of methane gas in the anaerobic digester are shown in Fig. 4.28 – 4.30.

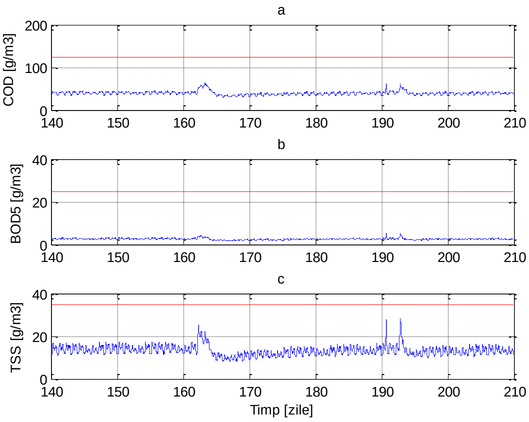


Fig. 4.28 - Variations in organic load for strategy S_2

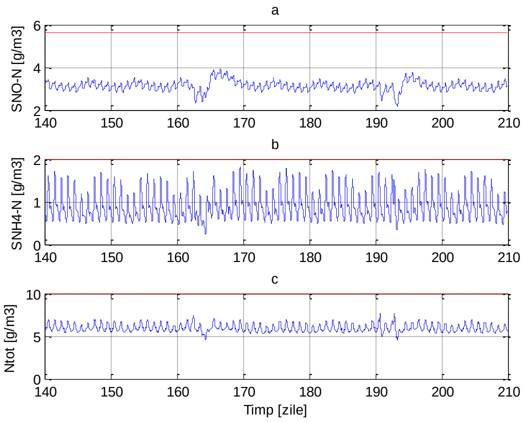


Fig. 4.29 - Nitrogen load variations for strategy S_2

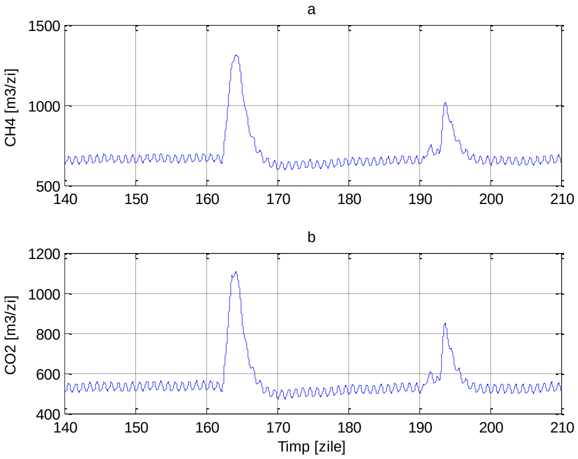
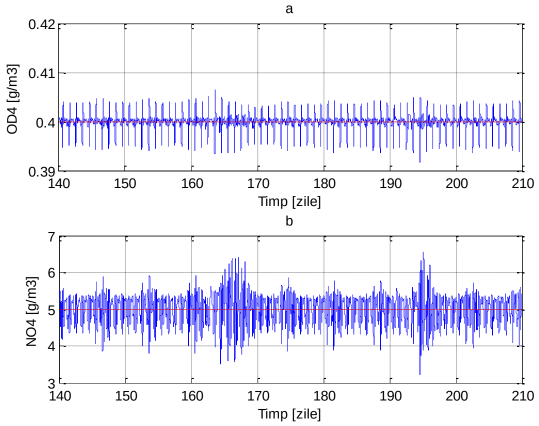


Fig. 4.30 - Production of CH_4 and CO_2 in the anaerobic digester in case of strategy S_2

The Fig. 4.26 – 4.27 shows the evolution of O_2 concentrations dissolved in basins B_5 and B_6 and of nitrate in basin B_4 at required references (4 mg/l and 1 mg/l respectively). It is observed that the above mentioned signals follow the required references. The values of the organic charges, *COD* and BOD_5, as well as the concentration of suspended solids, *TSS*, obtained from the effluent of the treatment plant under this strategy are below the legal limit imposed.

Strategy S_3 – Control of dissolved O_2 concentration in B_4, B_5, B_6 basins and concentration of nitrates in basin B_4 through internal recirculation

Within this strategy, basin B_1 is anaerobic, basins B_2 and B_3 are anoxic. These three basins are continuously mixed through the mixers. Basins B_4, B_5 and B_6 will be aerated, the dissolved oxygen reference for basin B_4 being set at 0.4 mg/l, and for basins B_5 and B_6 the dissolved oxygen reference is 2 mg/l. he output of the dissolved oxygen regulators is the command for the regulator valve on the blower air circuit. In basins B_4 the nitrate concentration is controlled by internal recirculation. The nitrate reference (NO_3) is 5 mg/l. The regulator output is the recirculated flow pump control command, similar to the previous strategy S_2. The amount of extracted excess sludge as well as the sludge extracted from the primary clarifier is set according to the same rules as for the S_2 strategy.



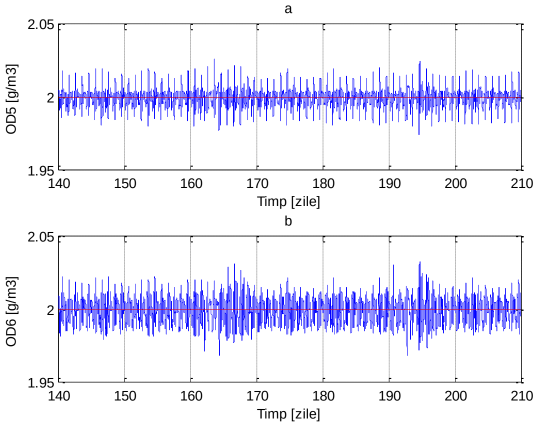


Fig. 4.32 - Adjustment of dissolved O_2 and nitrate concentration in basin B_4

Fig. 4.33 - Adjustment of dissolved O_2 in basin B_5 and B_6

For the last 70 days of the analysis, the variations of the effluent parameters and the production of methane gas in the anaerobic digester are shown in Fig. 4.34 – 4.36.

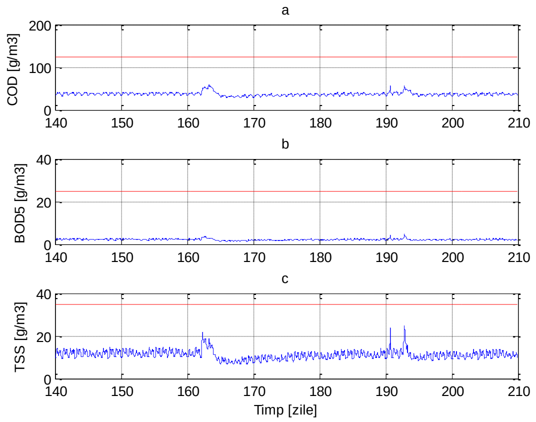


Fig. 4.34 - Variations in organic load for strategy S_3

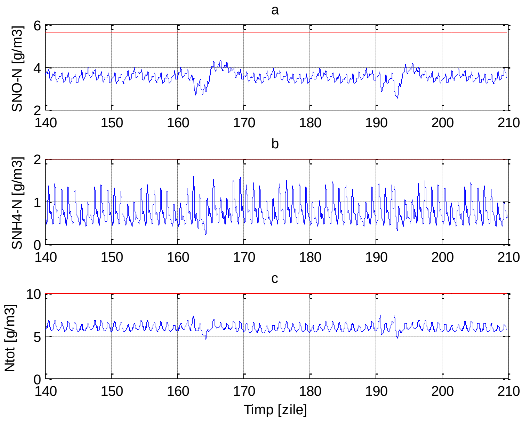


Fig. 4.35 - Nitrogen load variations for strategy S_3

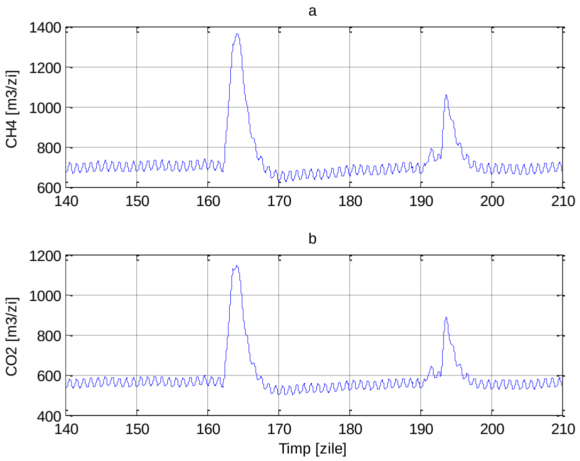


Fig. 4.36 - Production of CH_4 and CO_2 in the anaerobic digester in case of strategy S_3

The Fig. 4.32 – 4.33 shows the evolution of the dissolved O_2 concentrations in the B_4, B_5 and B_6 basins that follow the reference values of 0.4 mg/l (basin B_4) and 2 mg/l (basins B_5 and B_6) as well as the concentration of nitrates in basin B_4 (5 mg/l).

The values for organic charges, *COD* and BOD_5, as well as for the concentration of suspended solids, *TSS*, calculated from the effluent of the treatment plant under this strategy, are below the required legal limit. Flow disturbances due to rain and storm events lead to minimum variations in the calculated values observed on the charts for *COD*, BOD_5 and *TSS*, values that do not exceed the limits.

Strategy S_4 – Control of dissolved O_2 concentration in B_4, B_5, B_6 basins, concentration of nitrates in basin B_4 through internal recirculation and concentration of suspended solids at entry into the secondary clarifier.

Within this strategy, basin B_1 is anaerobic, and basins B_2 and B_3 are anoxic. These three basins are continuously mixed through the mixers. Basins B_4, B_5 and B_6 will be aerated, the dissolved oxygen reference for basin B_4 being 0.4 mg/l, and for basins B_5 and B_6 the dissolved oxygen reference is 2 mg/l. The output of dissolved oxygen regulator is the command for the control valve on the blower air circuit. In basin B4 the nitrate concentration is controlled by internal recirculation.

The nitrate reference (NO_3) is 5 mg/l. Regulator output is the command for the pump on the recirculated flow circuit, similar to the control strategy S_2.

The amount of sludge extracted from the primary clarifier is set to a constant value of 100 m^3/day. The concentration of the suspended solids at the entry into the secondary clarifier is also controlled.

The S_{MLSS} reference is set to 3500 g/m^3. MLSS regulator output is the command for the excess sludge pump. With the excess sludge, a part of the biomass that is important for the treatment process is also removed. The remaining quantity ensures the performance of the nitrification and denitrification reactions so that the concentrations of the effluent parameters do not exceed the legal limits. In Fig. 4.38 - 4.40 shows the evolution of the dissolved O_2 concentrations in the B_4, B_5 and B_6 basin following the 0.4 mg/l reference (basin B_4) and 2 mg/l (basins B_5 and B_6), respectively, of the concentration of nitrates in basin B_4 (5 mg/l), as well as that of *MLSS* at entry into the secondary clarifier.

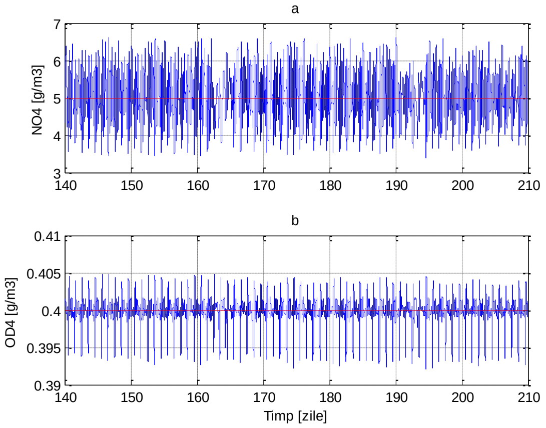


Fig. 4.38 - Adjustment of dissolved O_2 and nitrate concentration in basin B_4

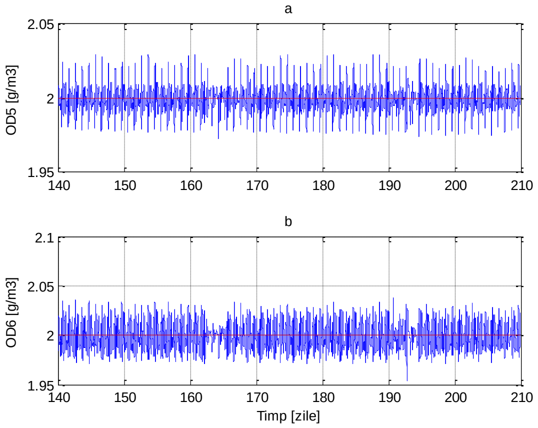


Fig. 4.39 - Adjustment of dissolved O_2 in basin B_5 and B_6

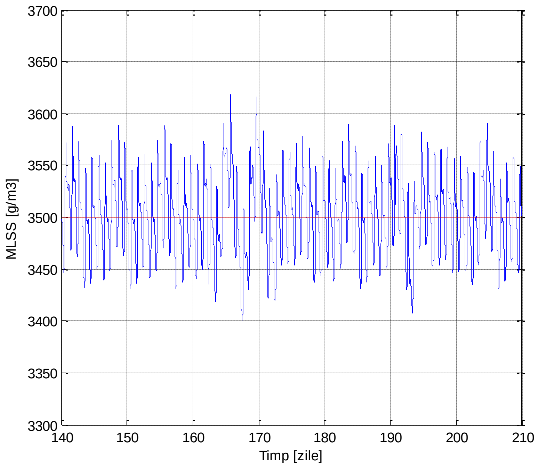


Fig. 4.40 - Adjustment of the *MLSS* concentration at the secondary clarifier entry

For the last 70 days analyzed, the variations of the effluent parameters and the production of methane gas in the anaerobic digester are shown in Fig. 4.41 – 4.43.

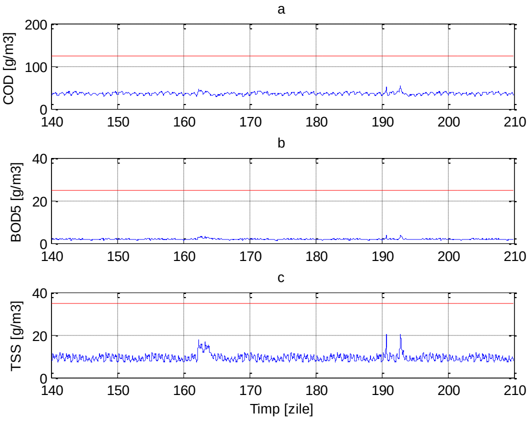


Fig. 4.41 - Variations in organic load for strategy S_4

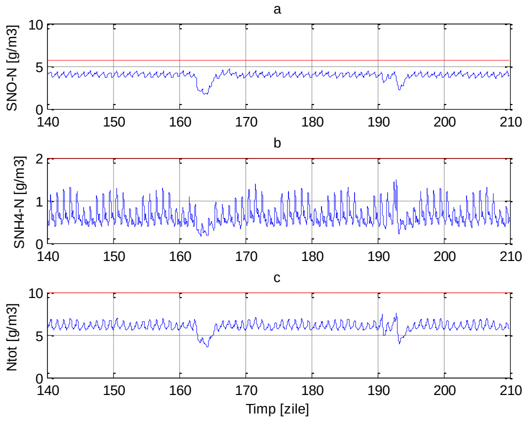


Fig. 4.42 - Nitrogen load variations for strategy S_4

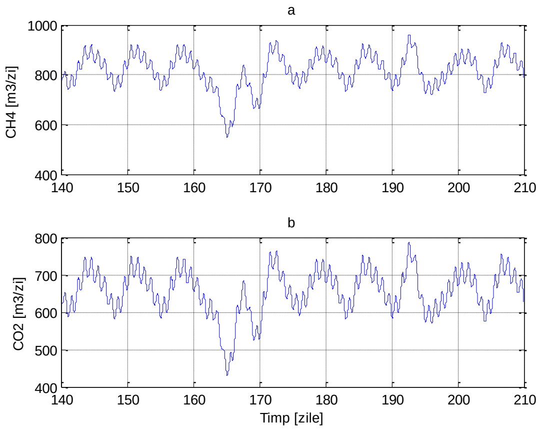


Fig. 4.43 - Production of CH_4 and CO_2 in the anaerobic digester in case of strategy S_4

The values for organic charges, *COD* and BOD_5, as well as for the concentration of suspended solids, *TSS*, calculated from the effluent of the treatment plant under this strategy, are below the required legal limit. The perturbations of the input flow due to rain and storm events lead to minimum variations of the calculated values which are observed on the charts for *COD*, BOD_5 and *TSS*, values that do not exceed the limits. The perturbations have a higher influence on nitrate nitrogen concentration, variations are observed but the maximum limits are not reached.

Strategy S_5 – Adjustment of dissolved O_2 concentration in B_4, B_5, B_6 basins and nitrate concentration in basin B_4 by internal recirculation and ammonium control in effluent.

Within this strategy, basin B_1 is anaerobic, and basins B_2 and B_3 are anoxic. These three basins are continuously mixed through the mixers. The basins B_4, B_5 and B_6 will be aerated, the dissolved oxygen reference for basin B_4 being 0.4 mg/l, and for basin B_5 the dissolved oxygen reference is 2 mg/l (Fig. 4.47). The dissolved oxygen reference in the B_6 basin will be given by the ammonium control loop (NH_4) of the effluent. The output of the dissolved oxygen regulators is the command for the regulating valve on the blower air circuit. In the B_4 basin the nitrate concentration is regulated by internal recirculation. The nitrate (NO_3) reference is 5 mg/l (Fig. 4.45). Regulator output is the recirculated flow pump control, similar to the control strategy S_2. The amount of excess sludge as well as the amount of sludge extracted from the primary clarifier is fixed at a constant value: for excess sludge the value is 360 m^3/day and for the sludge extracted from the primary clarifier the value is 100 m^3/day. The ammonium concentration in the effluent is adjusted using the *NH* loop set to the reference value of 1 mg/l, the ammonium concentration reading being read from the transducer located on the secondary diluent outlet line. The Ammonium Regulator (*NH*) output is a reference for the dissolved oxygen control loop dissolved in basin B_6 (Fig. 4.45 – 4.46). A larger amount of dissolved oxygen in basin B_6 leads to a decrease in the ammonium concentration of the effluent.

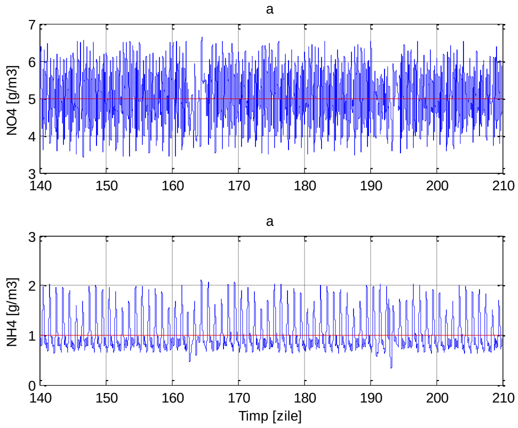


Fig. 4.45 - Adjustment of ammonium concentration in effluent and nitrate in B_4 basin

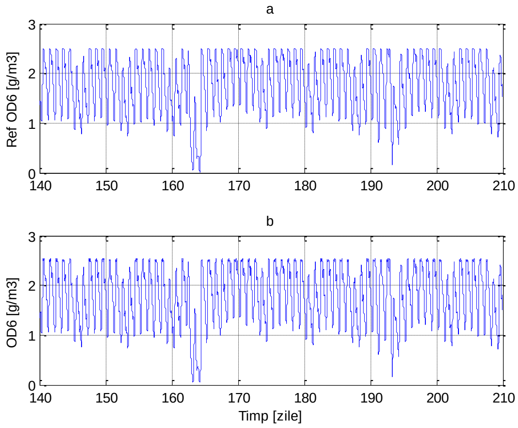


Fig. 4.46 – Reference and feedback for dissolved O_2 in B_6 basin

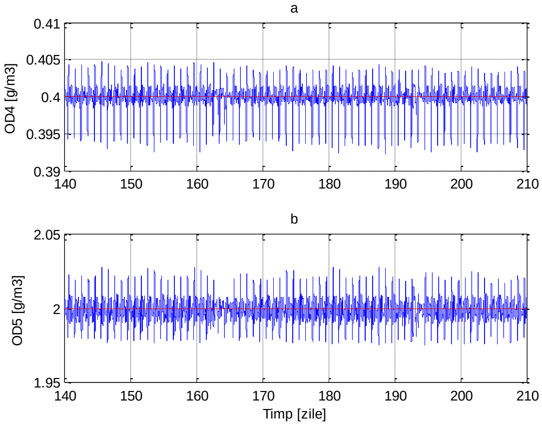


Fig. 4.47 - Adjustment of dissolved O_2 concentration in B_4 and B_5 basins

For the last 70 days analyzed, the variations of the effluent parameters and the production of methane gas in the anaerobic digester are shown in Fig. 4.48 – 4.50.

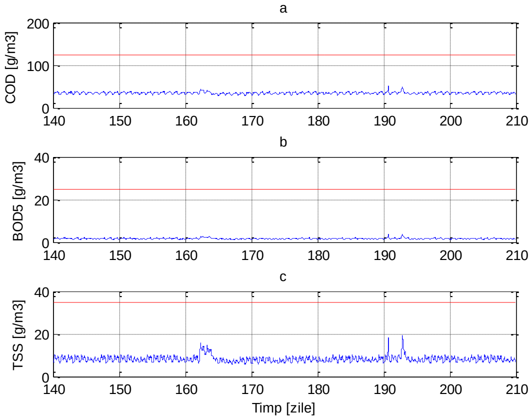


Fig. 4.48 - Variations in organic load for strategy S_5

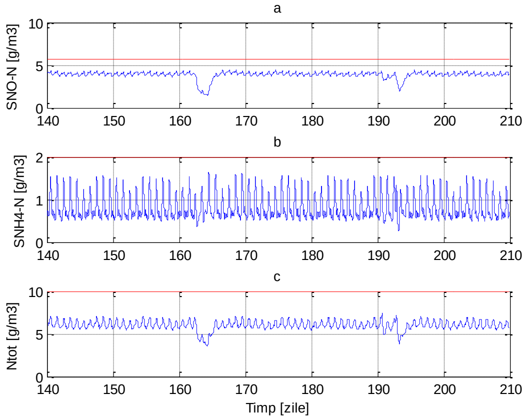


Fig. 4.49 - Nitrogen load variations for strategy S_5

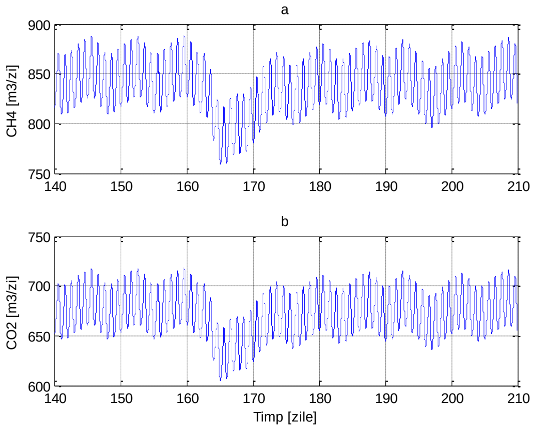


Fig. 4.50 - Production of CH_4 and CO_2 in the anaerobic digester in case of strategy S_5

The values for organic loads, *COD* and BOD_5, as well as for the concentration of solids in suspension, *TSS*, calculated for the effluent of the treatment plant under this strategy, are below the required legal limit. Total nitrogen is within acceptable limits, rain and storm events insignificantly alter nitrogen values. The control of dissolved oxygen in basin B_6 after the reference calculated by the ammonium regulator, rejects the disturbances that occur for the ammonium concentration due to rain events.

The conclusion is that each strategy can be applied in the sense that the limits of the quality indicators are respected, so the effluent corresponds to the quality standards in order to be discharged into the emissaries. Under these circumstances, it is recommended that the choice of the control strategy is based on the best cost / quality ratio.

4.4 The control strategies of the WWTP for reducing of phosphorus substances

For phosphorus removal, the treatment plant is modeled in SIMBA with the ASM2d model for biological reactors and secondary clarifier. The station model is similar to that shown in section 3.8 except that the anaerobic digestion part (model ADM1) is missing.

Similar to Fig. 4.21, is presented the transducers that measuring the following signals: dissolved oxygen concentrations, nitrates, ammonia, solid suspensions and phosphate as well as the following design elements: regulating valves, pumps located in areas where they are physically located technological flow of the treatment station. The addition of ferric chloride is carried out by means of the P_{FeCl3} pump at the entry of the secondary clarifier.

It is also considered that the treatment plant operating as normal with only two lines of four.

In this case, for the evaluation of control strategies, using the compound of the effluent, consisting of alternating periods of time dry, the rainy and stormy weather, as described in Section 4.3, for a total of 210 days. The analysis of the operation, the calculation of the indicators and the exceedances are done during the last 70 days of the 210 simulations.

Four control strategies were considered in which the implemented control loops use classical PI-type regulators as in the control schemes for reducing organic matter and nitrogen.

The four control strategies considered in this section are as follows:

1. An open loop control strategy;
2. A strategy that addresses the issue of the elimination of organic substances and nitrogen without taking into account the excess of the phosphorus component;

3. A strategy whose purpose was to remove phosphorus components without taking into account the limits of nitrogen concentration;
4. A combined strategy that takes into account all limitations on organic components for nitrogen and phosphorus;

Thus, from the operating point of the combined strategy, the process can migrate to the other points of operation, resulting in better efficiency for the removal of phosphorus or nitrogen, depending on the current system disturbances.

In conclusion, for the real influence considered, the S_4P strategy provides very low, subunit percentages for ammonium nitrogen with a maximum of 2.39 mg N/l for a single exceedance.

4.5 Control of the WWTP processes at optimal references

In the control strategies analyzed in previous sections, control laws have been implemented so that the treatment process ensures compliance with applicable effluent quality legislation to be discharged into natural receptors. Next, an optimization procedure has been approached which seeks to find the optimal references of the control loops in the scheme of the wastewater treatment plant, where the objective is to eliminate organic substances and nitrogen with its components (Fig. 4.21), without considering phosphorus removal processes.

Starting from the results obtained in [85], the situation was investigated in the case of the dissolved oxygen references in the B_4, B_5, B_6 basins and the nitrate reference in basin B_4 (NO_{B4}) having the internal recirculation rate as the control command.

A schematic of the control system (optimization) is shown in Fig. 4.77. It is noted that it is a hierarchical control scheme, in which the optimizer is on the upper level, and on the lower level the basic regulation loops mentioned in the previous paragraph.

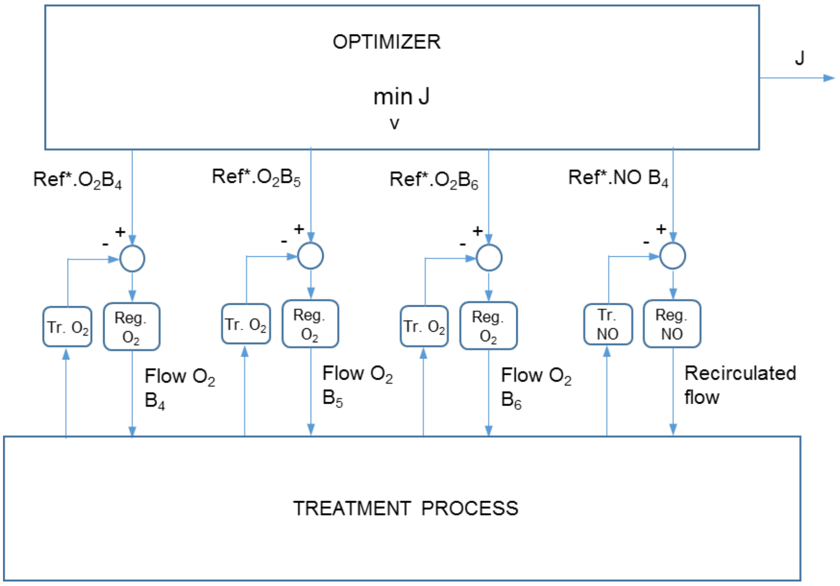


Fig. 4.77 - Systemic control scheme for the biological treatment process

For this situation, two optimization procedures were applied as follows:

a. The unidimensional search procedure of the optimal (coordinate relaxation method) in a modified (simplified) version so that the search for the extreme function criterion is done within a reasonable time. It should be noted that the integration of the process model takes about 4 minutes, the search time depending on the number of steps to the optimum point;
b. A stochastic optimization procedure that is based on generating random numbers at preset intervals to determine the desired references.

a. Searching for optimal references by the relaxation method

Search for optimal references for the treatment station scheme in Fig. 4.21 considering the following adjustment loops:

1. OD_4, $OD5$, $OD6$ – control loops for oxygen concentration dissolved in basins B_4, B_5, *and B6*. The coordinates corresponding to the starting point, from which the search for the optimal reference for the considered loops begins, are as follows: for OD_4, Ref_OD_4 = 0.5 mg/l, for OD_5, Ref_OD_5 = 2 mg/l, and for OD_6, Ref_OD_6 = 2 mg/l.
2. NO_{B4} – the nitrate concentration control loop by internal recirculation to adjust the nitrate value in basin B_4. The coordinate corresponding to the starting point is 5 mg/l.

The vector that searches for the optimum is:

$$V = [Ref\_OD_4\ Ref\_OD_5\ Ref\_OD_6\ Ref\_NO_4]^T \tag{4.1}$$

The external recirculated sludge flow rate is considered to be proportional to the inlet flow, the proportionality constant being k = 0.9. The excess sludge flow, transferred to the thickener and then to the anaerobic digester, is considered constant and has a value of 320 m^3 / day. The sludge flow from the primary clarifier is also constant and has a value of 60 m^3 / day. As explained in the previous paragraph, for each of the components of the reference vector, five points were considered as follows:

$$Ref\_OD_{4,0} = [0.2, 0.3, 0.5, 0.6, 0.8]^T \tag{4.2}$$

$$Ref\_OD_{5,0} = [0.8, 1.6, 2, 2.3, 2.5]^T \tag{4.3}$$

$$Ref\_OD_{6,0} = [0.8, 1.6, 2, 2.3, 2.5]^T \tag{4.4}$$

$$Ref\_NO_4 = [2, 2.8, 3.6, 4.4, 5.2]^T \tag{4.5}$$

The performance criterion considered has the following expression:

$$J = 0.5 \cdot EQ + OCI + 100 \cdot \left(N_{tot,p} + NH_{4,p} + TSS_p + COD_p + BOD_{5,p}\right) \tag{4.6}$$

where: EQ is the quality index of the effluent, OCI is the general cost index, $N_{tot,\ p}$ is the percentage exceedance of total nitrogen, $NH_{4,p}$ is the percentage exceedance of total ammonium, TSS_p - exceedance of the percentage of suspended solids, COD_p e is the exceedance percent of the chemical oxygen demand, and $BOD_{5,p}$ is the percentage exceedance of the biochemical oxygen demand parameter at five days.

The optimization problem can be formulated as:

$$\min_V J = 0.5 \cdot EQ + OCI + 100 \cdot \left(N_{tot,p} + NH_{4,p} + TSS_p + COD_p + BOD_{5,p}\right) \tag{4.7}$$

The algorithm ran three iterations, after which the stop conditions were met.

In Fig. 4.78 – 4.81 are represented, for each component of the reference vector, the results obtained in the three optimization iterations with the criterion calculated in those points, as well as the graphical representation resulting from the interpolation. The functions represented by interpolation are convex to the definition domain, which allows for the calculation of the minimum point coordinates. The red line in the graph corresponds to the first iteration, the blue color corresponds to the second iteration, and the green color corresponds to the third iteration. The global minima are marked with the diamond symbol. Criteria estimated for each iteration are obtained based on the coordinates of the minimum points (references corresponding to the minimum criteria) and the interpolation graph for each search direction. It follows:

$$J_{estimat1} = J\left(Ref\_DO_{4,min1}\ Ref\_DO_{5,min1}\ Ref\_DO_{6,min1}\ Ref\_NO_{B4,min1}\right) \tag{4.8}$$

$$J_{estimat2} = J\left(Ref\_DO_{4,min2}\ Ref\_DO_{5,min2}\ Ref\_DO_{6,min2}\ Ref\_NO_{B4,min2}\right) \tag{4.9}$$

$$J_{estimat3} = J\left(Ref\_DO_{4,min3}\ Ref\_DO_{5,min3}\ Ref\_DO_{6,min3}\ Ref\_NO_{B4,min3}\right) \tag{4.10}$$

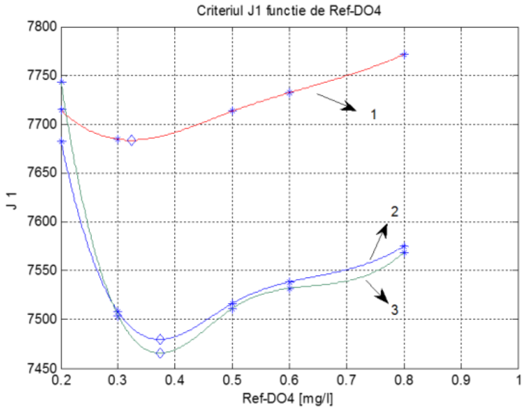


Fig. 4.78 - Optimization criterion for control loop OD_4

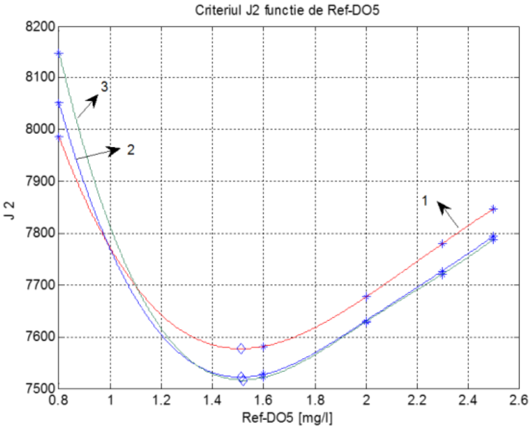


Fig. 4.79 - Optimization criterion for control loop OD_5

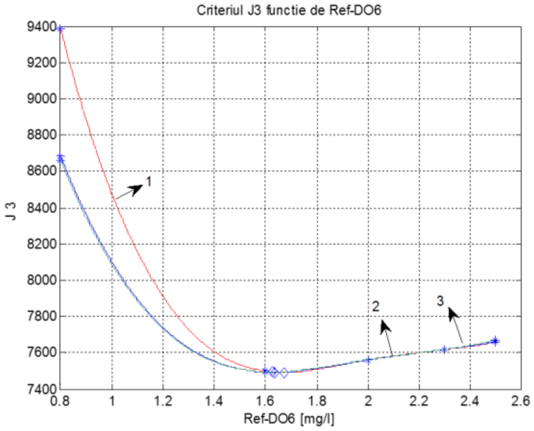


Fig. 4.80 - Optimization criterion for control loop OD_6

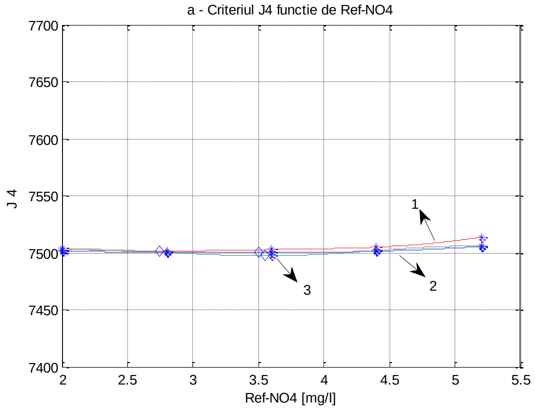


Fig. 4.81 – a - Optimization criterion for control loop NO_{B4};

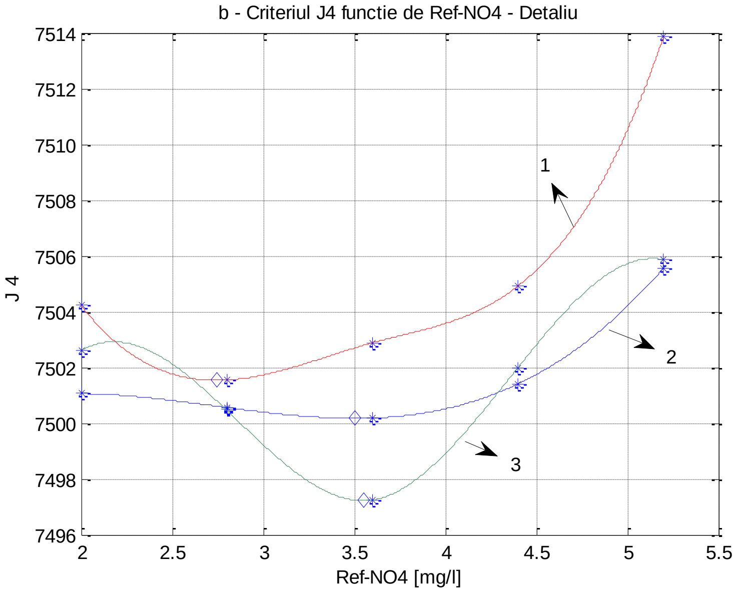


Fig. 4.81 – b - Optimization criterion for control loop NO_{B4} (Detail)

Observation:

In Fig. 4.78 – 4.81, J_i, with $i = 1 – 4$, is the value of the criterion J calculated on the i coordinate of the reference vector V. The numerical values obtained by the simulation are presented in the following table:

Table 4.9 - Minimum values of references and criteria

Nr.	$Ref\_DO_{4,min}$ [mg/l]	$Ref\_DO_{5,min}$ [mg/l]	$Ref\_DO_{6,min}$ [mg/l]	$Ref\_NO_{B4,min}$ [mg/l]	$J_{estimat}$	$J_{calculat}$
1	0.32	1.51	1.67	2.75	7501.5	7501.90
2	0.37	1.51	1.64	3.51	7500.2	7499.90
3	0.37	1.52	1.63	3.55	7497.2	7500.80

In the table 4.9 $J_{estimat}$ is the value of the criterion obtained using the interpolation curves, and $J_{calculat}$ is the value of the numerically calculated criterion using the coordinates of the minimum point. It can be seen that the differences are very small, which indicates that approximations through the interpolation curves are close to reality.

From Fig. 4.78 – 4.81 and Table 4.9 the following conclusions can be drawn:

- The search for optimal references was restricted at intervals according to the practice of control strategies (specific values - practical, based on technological considerations used in the treatment processes of a city of Galati dimension), the exceeding of these limits coming out of the practical feasibility area;
- The values of the coordinates of the minimum point (the criterion and the 4 references) differ insignificantly within the three iterations. The coordinate Ref_NOB4,min (see also Fig. 4.81 a and b), could be excepted, which shows that in this case the minimum is reached only in one iteration. From a geometric point of view, the isokriteria curves are similar to the semi-axes parallel to the coordinate axes (represented in the R4 space);
- The shape of the criterion is quite flat, at least for the NOB4. In other words, the variation of the nitrate reference in the B4 basin have a small influences for the criterion.

b. Search for optimal references by a stochastic method

In this method, the components of the reference vector, V, given by the relation (4.1), are searched, the criterion function being also used in the relaxation method, given by the relation (4.6). In principle, the method consists in randomly generating the V vector components, at each step being retained the "best" values of the point coordinates (criterion value + the four references), in the sense of decreasing the values of the criterion to a minimum. Stop algorithm is performed when it reaches the maximum number of iterations, N_{max}, in this case - 115 iterations. Intervals in which the references were randomly generated are those used in the previous method.

It should be noted that the method itself does not improve the simulation time, as it is known that in this method the result is even better as the number of iterations is higher.

The stochastic method has been used as an alternative to the relaxation method, since, as stated above, its modified version does not guarantee a sufficiently good accuracy.

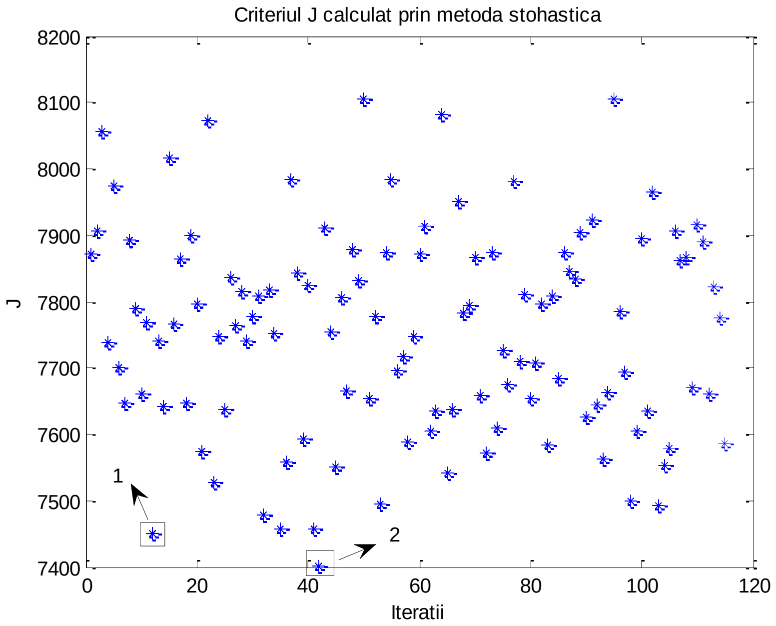


Fig. 4.82 - Optimization criterion for stochastic case

Table 4.11 - Minimum values of references and criterion for stochastic optimization

Nr.	*Ref_DO*$_{4,min}$ [mg/l]	*Ref_DO*$_{5,min}$ [mg/l]	*Ref_DO*$_{6,min}$ [mg/l]	*Ref_NO*$_{B4,min}$ [mg/l]	$J_{calculat}$
1	0.59	1.08	1.74	3.59	7450.90
2	0.69	0.83	1.59	2.54	7400.90

It is noted that lines 1 and 2 of Table 4.11 represent the coordinates of the points marked in the box in Fig. 4.82 (2 – the final minimum point and 1 – the previous value).

Chapter 5

Conclusions

Waste water treatment issues are extremely important for the development of human communities, ecosystems, and environmental conservation. The very existence of humanity is conditioned by the existence of clean water resources, unaffected by pollution. The importance of the domain is also due to the fact that waste water treatment is in the immediate attention of the European fora (the European Union, the European Commission) which has set forth a series of directives with the task of imposing very strict water quality legislation and maximum admissible pollution limits of the waste water to be discharged into the natural receptors.

If at first, the field of waste water treatment was observed technologically (it was considered only by chemists, biotechnologists, microbiologists, etc.) and basically its evolution was achieved only by finding new treatment technologies, now this domain has become interdisciplinary, with a close relationship with automation and computers domain. These areas, and especially the automation ones, have led to an increase in the efficiency of wastewater treatment processes by mathematical modeling methods and control of treatment processes. For automation engineers, the field of wastewater treatment has become a real challenge because biological treatment processes are very complex, highly nonlinear, affected by process and measurement noise, and also by parametric and model uncertainties (hidden dynamics - unshaped).

In essence, this doctoral thesis aimed to analyze, from a performance perspective, a process of biological waste water treatment for the treatment plant in Galati, a town with an average population in Romania of about 300,000 inhabitants. The treatment plant has as its main objectives the elimination of organic substances, nitrogen and its components as well as phosphorus. The three treatment steps are presented in detail: mechanical, bio-chemical and sludge. The wastewater treatment plant presented has a high degree of automation, being controlled with process computing equipment through a multi-level SCADA system - the highest level of monitoring, the control level of programmable machines and the level of field elements.

The mathematical modeling of the sewage treatment plant in Galati is addressed in the doctoral thesis. It is mathematically modeled in three stages:

1. The processes for the removal of carbon and nitrogen organic substances are modeled using the ASM1 mathematical model;
2. The ADM1 sludge treatment model (ADM1 model) is added to the ASM1 model, resulting in an aggregated mathematical model of the organic substance removal process along with the sludge treatment process, with the production of methane gas;
3. The phosphorus removal process is modeled by addition of ferric chloride to the mathematical model ASM2d.

Another issue addressed is the definition of the influent for the treatment plant model, based on the influent developed for the benchmark models (BSM), adapted to the design values of the treatment plant of the Galati municipality, in terms of the flow rate of the treated water and pollutant loadings in the three standard operating modes: dry weather, rainy weather and storm weather. The three mathematical models were analyzed at two operating points related to the treatment station: first, half of the maximum control values of the execution elements and the second, even at the maximum values of these values. It should be noted that the operation of the B-point treatment plant is limited by the maximum flow rates of the blowers (which provide the necessary oxygen) and of the pumps that ensure the flow rates, recirculation, etc.

Analysis of the results obtained by numerical simulation was made by comparing the evolutions of the main quality parameters with the maximum admissible limits provided by the legislation in force and based on the calculation of some quality indicators. Two conclusions are drawn from this analysis in Chapter 3 of the PhD thesis:

- Generally, in point A of operation there are significant exceeding at the main quality parameters;
- The operating point B shows improvement of the quality parameter values, meaning that the exceedances are smaller and rarer, but the calculated quality indicators show significant increases in energy consumption and, implicitly, costs.

As a general conclusion, for an efficient operation of the sewage treatment plant, it is necessary to implement suitable control methods within the automation system.

The last chapter of the doctoral thesis, Chapter 4, is dedicated to the control of the wastewater treatment plant in Galati. The design of control structures and laws was designed using a specific influent from Galati in terms of its properties (debits, charges, etc.) taking into account two important specific factors to the city at present (2017): the number of inhabitants and the degree of industrial development.

Control methods have been investigated for the following three situations:

1 the removal of organic substances and nitrogen together with its components (using the ASM1 and ADM1 models);

2 phosphorus removal (on the ASM2d model);

3 control at the optimal reference for the process of reducing organic substances and nitrogen;

In all analyzed cases, a comparative approach to several control strategies using the same type of regulation law (in the present case PI regulation laws) was considered more useful than the use of several control techniques. This is because, at the level of the whole system, parameters and quality indicators are mostly influenced by the choice of references and operating points in which the treatment processes take place. For the first case (elimination of organic substances and nitrogen), 5 control strategies were tested and for the second case (elimination of phosphorus) - 4 control strategies. In both cases, the first strategy was in the open loop, in order to have a comparison term and to evaluate the effectiveness of control strategies. In both situations an improvement of effluent parameters was observed, in compliance with the norms and the legislation in force regarding its quality.

The last part of the chapter describe the control of the waste water treatment process at optimal references. The method was addressed in order to take into account a number of other indicators, such as costs and energy consumption, important indicators for a high-capacity treatment plant, such as the city of Galati. Two optimization methods have been analyzed:

a. a one-dimensional (relax) search method in a modified version;

b. a method of stochastic optimization;

The optimization was performed for the references of the dissolved oxygen loops in the B_4 – B_6 basins and the nitrate reference in the B_4 basin The results showed that the variation of the criterion is insignificant as value for variation of the fourth coordinate (the nitrate reference in basin B_4) and so was searched the optimal point coordinates relative to a reduced reference vector without the reference for the nitrate loop in basin B_4, which has been kept constant. The results obtained were similar to those in the previous case, the value of the criterion being very close to the previous values.

It should also be noted that the first method (the one-dimensional modified search) contains a series of approximations (e.g., determining the minimum in one direction by 5 points, approximating the curve of the criterion by an interpolation curve, etc.) which does not guarantees an point of optimum due to errors introduced by the used method. Therefore, a second method has been approached (stochastic one) which has allowed a point of minimum with lower error computations compared to the previous method.

5.1 Original contributions

The doctoral thesis contains the following original contributions:

Chapter 2:

1. Analysis of the wastewater treatment plant in Galati from the perspective of the technological structure, the automation equipment and the flows of the influent and the loads with organic substances, nitrogen and phosphorus.

Chapter 3:

2. Determination of the influent for the wastewater treatment plant in Galati starting from the influent from BSM1, calibrated on the design data values of this treatment plant, specific to the three operating regimes: dry weather, rainy weather and storm weather for the elimination of organic substances and nitrogen.
3. Determination of the influent for the wastewater treatment plant in Galati, modeled with processes for the removal of phosphorus in the three operating regimes mentioned in point 2.
4. Mathematical modeling of the biological treatment line (basins + secondary clarifier) for the elimination of organic substances, nitrogen and its components (nitrates, nitrites, and ammonium) with the ASM1 model.
5. Validation of the mathematical model from point 3 in SIMBA simulation environment.
6. Extending the biological treatment line model by adding the mathematical model of the anaerobic sludge fermentation process for methane gas production (ADM1 model).
7. Validation of the extended model (ASM1 + ADM1) in SIMBA simulation environment.
8. Modeling of the wastewater treatment plant in Galati municipality with processes for phosphorus removal by addition of ferric chloride, with the model ASM2d.
9. Validation of the mathematical model from point 7 in SIMBA simulation environment.
10. Analyzing the performance of the treatment station (the quality of the influent, the cost index, the number of exceedances of the limits, etc.) at two operating points: the first one at the maximum of the control elements of the execution elements and the second even at the maximum values of these values. The analysis concerns both the elimination of organic substances and nitrogen and phosphorus.

Chapter 4:

11. Determining the current influent (based on experimental data from 2017) used in models for the removal of organic substances and nitrogen and for the removal of phosphorus.
12. Design, validation in SIMBA simulation environment and comparative analysis of five strategies for the elimination of organic substances and nitrogen together with its components (nitrates, nitrates, ammonium).
13. Design, validation in SIMBA simulation environment and comparative analysis of four strategies for phosphorus removal case.
14. Optimizing the process of elimination of organic substances and nitrogen by determining the optimal reference for the loops to control dissolved oxygen concentrations in basins 4, 5 and 6 and the nitrate concentration by internal recirculation by two methods: 1. the method of relaxation in a simplified version and 2. a stochastic method.

5.2 Future research directions

The PhD Thesis opens a number of new research directions in the field of modeling and control of biological waste water treatment processes, as follows:

1. Modeling and simulation of the plant using a global mathematical model of biological waste water treatment processes that integrates the elimination of organic substances, nitrogen with its components (nitrates, nitrites, and ammonium) and phosphorus.
2. Design and implementation of advanced control laws for the control of biological wastewater treatment processes.
3. Establishing a "more sensitive" optimization criterion for certain references of control loops in the structure of a biological wastewater treatment plant.
4. Optimizing the biological treatment of wastewater for other references, e.g., extraction of sludge from secondary clarifier and sludge from the primary clarifier.
5. Developing a hierarchically superior control structure for computing and optimizing online or offline the reference for control loops at strategies applicable to the wastewater treatment plant.

List of papers

- Papers published in the doctoral thesis field**:**

1. **Luca L.**, Barbu M., Caraman S., *Modelling and performance analysis of an urban wastewater treatment plant*, Published in System Theory, Control and Computing (ICSTCC), 2014, 18th International Conference, pp. 285 – 290, DOI: 10.1109/ICSTCC.2014.6982430, 2014 (indexed ISI proceedings).
2. **Luca L.,** Barbu M., Ifrim G., Caraman S., *Analysis of phosphorus removal performances in a municipal treatment plant*, Published in System Theory, Control and Computing (ICSTCC), 2015, 19th International Conference, page. 415 – 420, DOI: 10.1109/ICSTCC.2015.7321329, 2015 (indexed ISI proceedings).
3. **Luca L.**, Barbu M., Ifrim G., Ceangă E., Miron M., Caraman S., *Fuzzy Control of a Microalgae Growth Process in Photobioreactors*, Published in System Theory, Control and Computing (ICSTCC), 2018, 22th International Conference, Sinaia, România, 2018 (indexed IEEExplore, indexing ISI proceedings).
4. Chiroşcă A., Dumitraşcu G., **Luca L.**, Caraman S., *Fuzzy control of the activated sludge wastewater treatment process treated as multivariable process*, The Annals of „Dunărea de Jos” University of Galaţi, Fascicle III Electrotechnics, Electronics, Automatic Control, Informatics, 34(2): 1-5, ISSN 1221-454X, 2011.
5. Chiroșcă A., **Luca L.,** Ifrim G., Caraman S., *Robust control of the biological wastewater treatment process*, Published in System Theory, Control and Computing (ICSTCC), 2013, 17th International Conference, pag. 113 - 118, DOI: 10.1109/ICSTCC.2013.6688945, 2013 (indexed ISI proceedings).
6. **Laurențiu Luca**, George Ifrim, Emil Ceangă, Sergiu Caraman, Marian Barbu, Ignacio Santin, Ramon Vilanova, *Optimization of the Wastewater Treatment Processes Based on the Relaxation Method*, The 5th International Symposium on Electrical and Electronics Engineering (ISEEE - 2017), Galați, 20 - 22 October, România, 2017 (indexed ISI proceedings).
7. Miron M., Frangu L., **Luca L.**, Caraman S., *Artificial Neural Network Approach for Fault Recognition in a Wastewater Treatment Process*, Published in System Theory, Control and Computing (ICSTCC), 2018, 22th International Conference, Sinaia, România, 2018 (indexed IEEE xplore, indexing ISI proceedings).
8. **Luca L.**, Barbu M., Ifrim G., Ceangă E., Caraman S., *Control Strategies of a Wastewater Treatment Plant*, 12th IFAC Symposium on Dynamics and Control of Process Systems, including Biosystems, April 23 – 26, 2019, Florianopolis, Brazil (Paper under evaluation).

- Papers published in the industrial automation field:

1. Iulian Nacu, **Laurențiu Luca**, Nicu Roman, and Dorel Aiordăchioaie, *On VIBROMOD - An Electronic Equipment for Data Vibration Measurement and Analysis*, The 22nd IEEE International Symposium for Design and Technology in Electronic Packaging (SIITME-2016), Oradea, 20-23 October, 2016 (indexed ISI proceedings).
2. Bogdan Theodor, Anamaria Tiron, George Marinescu, Iulian Nacu, **Laurențiu Luca**, Nicu Roman and Dorel Aiordăchioaie, *A Multi-level Software Solution for Process Monitoring and Diagnosis*, The 5th International Symposium on Electrical and Electronics Engineering (ISEEE - 2017), Galati, 20 - 22 October, Romania, 2017. Special Session “Change Detection In Vibrational Processes" (indexed IEEExplore).

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