Babeș-Bolyai University of Cluj-Napoca

Faculty of Chemistry and Chemical Engineering

Doctoral School of Chemical Engineering

PhD THESIS

Mathematical modeling of processes in wastewater treatment plants.
Applications of the mathematical model ASM1 + ADM1

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Content:

Chapter 1. General aspects

1.2. Introduction. Motivation of the chosen theme

Council Directive 91/271 / EEC of 21 May 1991 on Urban Wastewater Treatment, as amended and supplemented by Commission Directive 98/15 / EC on 27 February 1998, is the legal basis for Community waste water legislation. Directive 91/271 / EEC on Urban Waste Water Treatment has been fully transposed into Romanian legislation by Government Decision no.188 / 2002 for the approval of the norms regarding the discharge conditions of waste water in the aquatic environment, modified and completed with the Government Decision no. 352/2005.

Wastewater treatment plants operate on the basis of Environmental Authorizations and Water Management Permits. The overcoming of quality indicators in treated water leads to the application of financial penalties directly proportional to the amount of pollutant discharged, according to the "polluter pays" principle, according to O.U.G. 195 / 22.12.2005, Art. 94, letter i.

In the context of increasingly restrictive environmental legislation on urban waste water treatment, new water management problems arise. Improving the quality indicators of the treated water at the discharge into the emissary, implicitly leads to the generation of larger quantities of separate sludge.

Water purification, treatment and disposal of produced sludge are carried out with high operating costs. Economically, in addition to operating costs (daily, monthly or yearly), some "performance indicators" have also been defined:

- Cost (RON, EURO, etc.) / m^3 purified water;
- Electricity consumption (kWh) / m^3 purified water;

In operation, operators of WWTPs (wastewater treatment plant) are continually challenged to improve these economic indicators.

The implementation of advanced control techniques (model predictive algorithms, fuzzy logic, neural networks, hybrid systems, etc.) in the management and optimization processes in WWTPs leads to lower operating costs.

Also, the use of additional streams in municipal wastewater treatment plants, either in fermentation digesters or in water treatment basins, may lead to additional revenues for treatment plants (water-channel companies), implicitly to the decrease operating costs.

In this situation, water-channel companies can broaden their spectrum of activity, becoming authorized economic operators in the disposal of certain types of waste.

The present thesis aims to bring new information useful to operators in the treatment plants, to provide data on how to use biodegradable waste, to propose recovery solutions so that this operation is carried out in a controlled and not empirical way , using the mathematical models proposed by the International Water Association (IWA).

1.3. Waste. National and European legislative framework

The waste directive of the European Commission 75/442 / EEC gives the legal definition of waste: By "waste" is meant any object or substance [...] which its owner throws or intends to discard." [1]

In the EU's 28 countries, 2.32 billion tons of municipal waste were generated in 2017, of which 59.28% were treated and 40.72% were stored. For the European Union there has been a significant increase in the share of recycled or composting municipal waste, from 18% in 1995 to 46% in 2017. Romania is deficient in this area, managing to recycle only 4.2% and 172 million tons of municipal waste generated. Romania continues to store 92.75% of municipal waste generated [2].

In order to reach the 50% recycling target imposed by the European Union in 2020, Romania needs to make a special effort. Authorities will have to consider an improvement in waste management legislation, as the current overall cost of landfill is influenced only by pitfall, not a storage charge implemented by the central / local government. [6]

1.4. Current state. Examples of good international practices for the use of biodegradable waste in municipal wastewater treatment plants

For a sustainable society, which wants to produce chemicals from renewable resources, especially from waste streams, emerging biotechnologies are important. Efforts are now being made to eliminate organic pollutants as far as possible without external energy sources. For these reasons and following the implementation of the IPPC Directive 96/61 / EC, Waste Water and Waste Gas Treatment Directive, which recommends the determination of the best available techniques, the use of anaerobic fermentation plants in sewage treatment plants for water treatment in the agro-food industry, waters with high biodegradable loadings. [9], [10].

Consequently, in recent years, anaerobic fermentation plants in WWTPs have evolved into consolidated technologies for the treatment of medium and large-scale water in food industries. [11], [12].

1.5. Thesis objectives

In recent years, modeling and process simulation has gained a strong development. Based on the mathematical model, simulation, you can try an evolved leadership solution without investing money before you get the prospect of good results. The modeling of chemical processes is also being extended to areas of chemical engineering, polymers and biotechnologies, which have no modeling traditions [21]. Water treatment and sludge treatment are based on biotechnology.

The International Water Association (IWA) proposes through the Mathematical Modeling Group for the design and operation of sewage treatment plants several mathematical models for active sludge treatment plants: ASM1, ASM2, ASM2d, ASM3. For the design and exploitation of fermentation digesters proposes mathematical model ADM1.

The benefits of using a mathematical model are as follows:

- Estimates the future evolution of the process as an input size changes;
- It is possible to test what is the process response under the operating conditions;
- Can be trained with process data;
- By simulating the mathematical model one can try an evolved leadership solution;
- Can provide useful information to those who lead such processes;
- Can be used to train and improve operators;
- Can be implemented in the automated driving process, reducing the amplitude of the disturbances;
- It can bring economic benefits;
- Can replace the experience of the "experienced operator"

In this thesis I propose, for a municipal wastewater treatment plant, to develop the BSM1- mathematical models for the water treatment line connected to an ADM1- model for the sludge treatment line. This thesis also wants to answer some of the questions that water companies ask:

- Can water-channel operators become authorized economic agents in the disposal of biodegradable waste? What would be the criteria for waste selection?
- What is the energy potential or correction of biodegradable waste?
- Can some waste be utilized and disposed of in fermentation digesters or in water treatment basins in treatment plants?
- Can water-channel operators get extra income from the disposal of these wastes in sewage treatment plants?

• Can the economic parameters of the operation of the treatment plants improve, implicitly reduce the costs by accepting additional flows?

• How much would the percentage of electricity recovered from the sewage treatment plant through the treatment of waste increase, in the context in which purification plants tend to recover almost entirely the energy consumed in water treatment by alternative electric power generation?

• What is the effect of the internal return water, rich in ammonia, on the treatment process?

• What is the effect of temperature variations on the quality of biomass treatment water?

Chapter 2. Treatment processes in wastewater treatment plants

2.1. Wastewater treatment with active sludge. Biological removal of carbon, nitrogen (nitrification / denitrification) and phosphorus. Chemical precipitation of phosphorus

The active sludge treatment process is the most used, and probably the most versatile and efficient of all treatment processes. Elimination of pollutants is done biologically, using microorganisms (biomass) that decompose or remove organic matter. The process involves the use of at least one secondary aeration and secondary decanting tank, hydraulically connected to allow biomass recirculation [23]. Biomass has about 95% of bacteria and 5% of protozoa, mites, fungi, algae and viruses [24].

The treatment plant may or may not be equipped with an advanced biological treatment system. The removal of nitrogen and phosphorus from wastewater is most often carried out in the same basins where organic biodegradable substances are removed. Establishing aerobic and anaerobic conditions in a controlled manner allows the development of biomass capable of accomplishing organic matter removal, nitrogen removal (nitrification and denitrification) and phosphorus removal [27].

The process of producing autotrophic organisms (producing themselves the substances they need) and heterotrophic organisms (which feed on organic substances only, lacking the ability to synthesize organic substances from inorganic substances).

2.1.1. Water Quality Parameters

Purified water and wastewaters are characterized by the following physical and chemical parameters: temperature, pH, suspended matter (MTS, TSS), biochemical oxygen demand for 5 days (BOD5), chemical oxygen demand (COD), total nitrogen (N), ammonium nitrate (NH4 +), nitrates (NO3-), nitrates (NO2-), sulphides and hydrogen sulfide (S2-), sulphites (SO32-) P), chlorides (Cl-), metals (As, Al, Ca, Pb, Cd, Cr, Fe, Cu, Ni, Zn, Hg, Ag, Mo, Se, Mn, in organohalogenated, organostannic and organophosphorus compounds, substances with carcinogenic properties, organic compounds of mercury, organosilicon compounds or radioactive waste according to the relevant legislation [36].

BOD5 (*biochemical oxygen demand*) and COD (*chemical oxygen demand*) are the most commonly used parameters for characterizing the organic carbon content of wastewater.

2.2.2. Control and management of water treatment processes with active sludge

Wastewater Treatment Plants (WWTPs) are urban infrastructures that reproduce in an intensified manner the biochemical degradation processes occurring naturally in rivers. High operational costs encourage the use of advanced control strategies to optimize performance and reduce energy consumption. The implementation of advanced control strategies is generally limited by the incomplete data sets measured in the treatment plant. Also, the implementation of advanced control strategies can be limited by the lack of real data from certain limit scenarios (torrential rains, low temperatures, accidental sewerage, etc.). [38].

A basic control involves the monitoring of a limited number of sizes, in general: the volume of waste water processed, the concentration of dissolved oxygen in the reactor, the concentration of reactor suspensions and the physicochemical evacuation (with the frequency required by the regulatory act (authorization)).

An advanced control involves the pursuit of a much greater number of sizes: the physicochemical characteristics of the wastewater entering the treatment plant and the biological reactor (pH, temp., BOD5, COD, N_{total}, NO3-, NO2-, NH4 +, P_{total} , MTS, etc.), recirculation and evacuation volumes, concentrations of NO3 - at the exit of the biological reactor, the volumes of sludge discharged from the system, etc.

The control strategies that can be implemented can be basic (On-Off, PI / PID) or advanced (MPC, fuzzy logic or neural networks). In the implemented management strategy, the process can be adjusted *before or after the disturbance*.

2.2. Anaerobic fermentation of sludge

Elimination of pollutants from wastewater in treatment processes in treatment plants generates significant amounts of sludge. Sludge are non-homogeneous liquids composed of microorganisms and solid particles separated in the lower part of the decanters by sedimentation processes. Thus, the activity of the treatment plants is divided into two directions: on a waste water treatment line, or another sludge treatment line in order to reduce the volumes of waste generated.

One of the sludge treatment processes is anaerobic fermentation. Anaerobic fermentation is a process of microbiological decomposition of organic matter in the absence of oxygen, resulting in a mixture of gases (biogas) and sludge liquor. The oldest and most widespread application of anaerobic fermentation is the treatment of sewage sludge. It is an efficient process of environmental pollution that produces renewable energy, the main component of which is methane. Anaerobic fermentation has grown significantly since the first energy crisis of 1970 and can now be considered a mature technology. It has become very popular in recent years because it is capable of generating energy from waste. [15]

Anaerobic fermentation is a very complex process, intensively researched in the last period, the following topics being of interest to the researchers: reaction mechanisms, reactants, inhibitors, sludge pretreatment techniques, new additives, reaction conditions, reactor constructions, reaction or the microbial community.

The anaerobic fermentation mechanism has four steps and can be schematically represented:

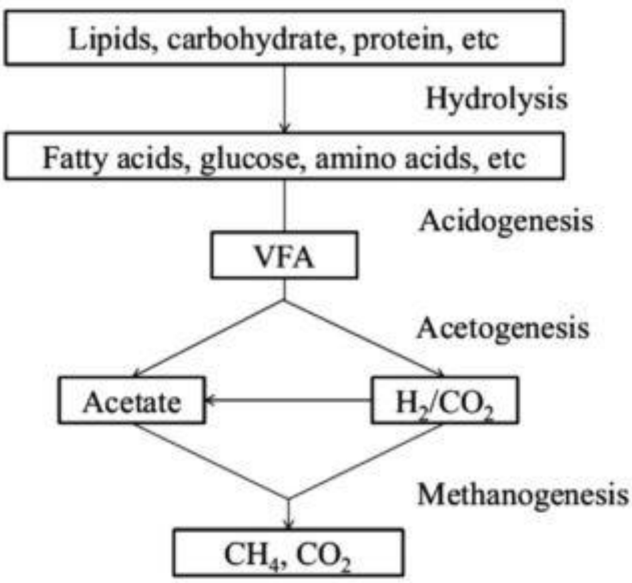


Fig. 1 Mechanism of anaerobic fermentation [14]

2.2.1. Factors influencing fermentation

1. Temperature
2. pH, alkalinity and VFA concentrations
3. Retention time
4. C: N: P ratio (substrate quality)
5. OLR (organic loading rate)
6. Moisture in the reactor
7. Ammonia
8. Internal Mixing
9. Toxic Inhibitors

2.2.2. Control and management of anaerobic fermentation

New process analyzers are part of a new paradigm. It can be said that the future of the monitoring process is facing a paradigm shift. The construction in the treatment plants of large volume fermenters, volumes that act efficiently as a buffer and guarantee the quality of effluents, is no longer attractive. By correctly applying modern sensors and multivariable data analysis technologies, the process can be kept within specifications, even at significantly higher loadings than today. Analytical Technology Processes (PAT) and Sampling Theory (TOS) have great potential in developing monitoring and control of the anaerobic fermentation process. [96]

Anaerobic fermentation is very sensitive to process disturbance, and it is great to use online monitoring and control techniques for efficient operation. The implementation and the advantage of the new strategies are highly researched by researchers

Electrochemical, chromatographic and spectroscopic devices are used to monitor and control the process on-line. The complexity of the new control strategies ranges from feedback adjustments (after disruption) to advanced control systems.

A basic monitoring (basic control) involves tracking the fundamental operating parameters: biogas production, sludge flows, pH, temperature, redox potential and substrate composition. Advanced monitoring involves tracking some parameters that may indicate process disturbances (VFA, alkalinity, ammonia, hydrogen, etc.). While the basic sensors offer a robust operating method, complex sensors / analytical instruments (chromatography, spectroscopy) are valuable in process control. [97]

The control strategies that can be implemented can be basic (On-Off, PI / PID) or advanced (fig.33). The control strategy can implement an adjustment before or after the disturbance.

2.3. Biogas production and applications

Maximizing the production of biogas in anaerobic digestion can minimize the total operation costs of the treatment plant. Biogas is a green energy source (electricity and heat production, fuel source). Without further treatment, biogas can only be used at the place of production. Subsequent treatments aim to increase the calorific value of biogas and transport it over longer distances, provided it is economically profitable. Compressing and using gas cylinders or introducing gas into the gas transport network are the targets of the treatment process. This requires the removal of CO_2 and contaminants from biogas.

With a calorific value of 21-25 MJ / m^3, biogas is 30-40% lower than natural gas, which has a calorific value of 37.3 MJ / m^3 [40]. Biogas is an excellent fuel for a large number of applications and can also be used as a raw material for the production of other chemical compounds. Biogas can be used more or less in all applications developed for natural gas.

Biogas is also the ideal fuel for co-generation units (CHP). Turbine gas (micro-turbines, 25-100kW and large turbines, >100kW) with low emissions, low maintenance costs and comparable efficiency to spark-ignition engines are used. Efficient production and use of biogas can significantly reduce the carbon footprint of sewage treatment plants. If sludge generated in processes is properly collected and efficiently managed, the plant can generate substantial biogas energy so as to become a net energy producer rather than a consumer [13]. In Europe, the annual potential of biogas production is estimated at over 200 billion cubic meters [61]. Daily production of biogas in the new treatment plants in Europe where co-fermentation is practiced ranges from 2.5 to 4.0 m^3 of biogas / m^3 reactor, and in the United States only fermentation yields between 0.9 and 1.1 m^3 biogas / m^3 reactor [99].

Chapter 3. Mathematical modeling of processes in wastewater treatment plants

3. 1. Brief History of Mathematical Modeling for Treatment Processes in Wastewater Treatment Plants

It is difficult to evaluate and optimize the control parameters in the treatment plants in real situations. One solution may be to build and use dynamic models and simulators to design, test and evaluate control strategies [101].

Efforts over the last 40 years by the scientific community working in the field of waste water treatment have resulted in the development of mathematical modeling for sewage treatment processes. The development of knowledge on treatment processes as well as the design, control and management of treatment plants were pursued.

The interest was mainly focused on two complementary scientific areas in the treatment plants:

- On-line control and automation tools (ICA);
- Mathematical modeling of processes. [102]

In 1982, the International Association for Research and Control of Water Pollution (IAWPRC) formed a working group on mathematical modeling for the design and operation of active sludge processes. From 1982 to the present, mathematical modeling has evolved widely and has been combined with the development of control systems. The knowledge gained over the years has led to the evolution of models from a simple growth-based kinetics, such as active mud models (ASM1), to more complex models such as ASM2d (22). Furthermore, mathematical models have been developed to describe the physical separation processes that are performed in the sewage decanters [104].

For the sludge treatment line, the "Anaerobic Digestion Modeling Working Group" of the International Water Association (IWA) has developed the Anaerobic Digestion Model no. 1 (ADM1) [105] to arrive at a common basis for further development of the model.

3. 2. ASM1 (Model No. 1 with active sludge)

ASM1 (*Activated Sludge Model No. 1*) is the most widely accepted and used model by the scientific community for both Continuous and Sequential Reactors (SBR). The model was developed by Henze & collaborators in 1987, a working group reunited by *the IWA Task Group on Mathematical Modeling for the Design and Operation of Biological Wastewater Treatment*. The ASM1 model describes the processes of nitrification and denitrification without describing the biological removal of phosphorus. The model is based on two types of bacteria: heterotrophies and autotrophs. Basically, *8 basic biochemical processes* are described. The model uses *13 different compounds (state variables),* and the behavior of each compound is described in a non-linear differential equation.

In the ASM1 model, carbon compounds are decomposed as shown below:

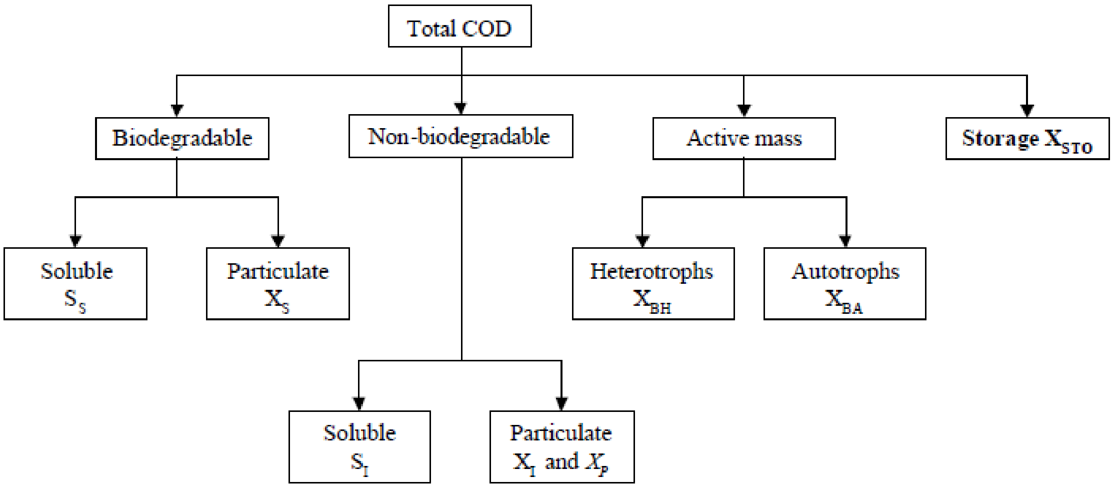


Fig. 2. Carbon compounds characteristic of wastewater [115]

Note: Note: S = soluble compound, P = particulate compound;

In the ASM1 model, nitrogen compounds are decomposed as shown below:

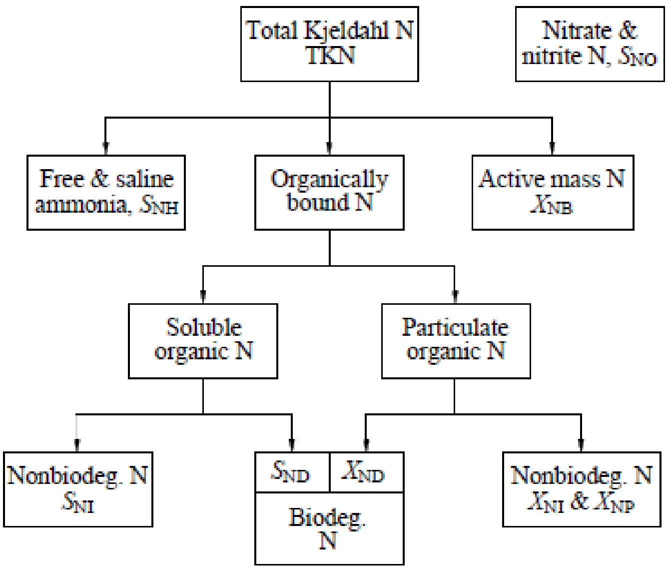


Fig. 3. Nitrogen compounds characteristic of wastewater [115]

The process can be schematically reproduced in the following figure:

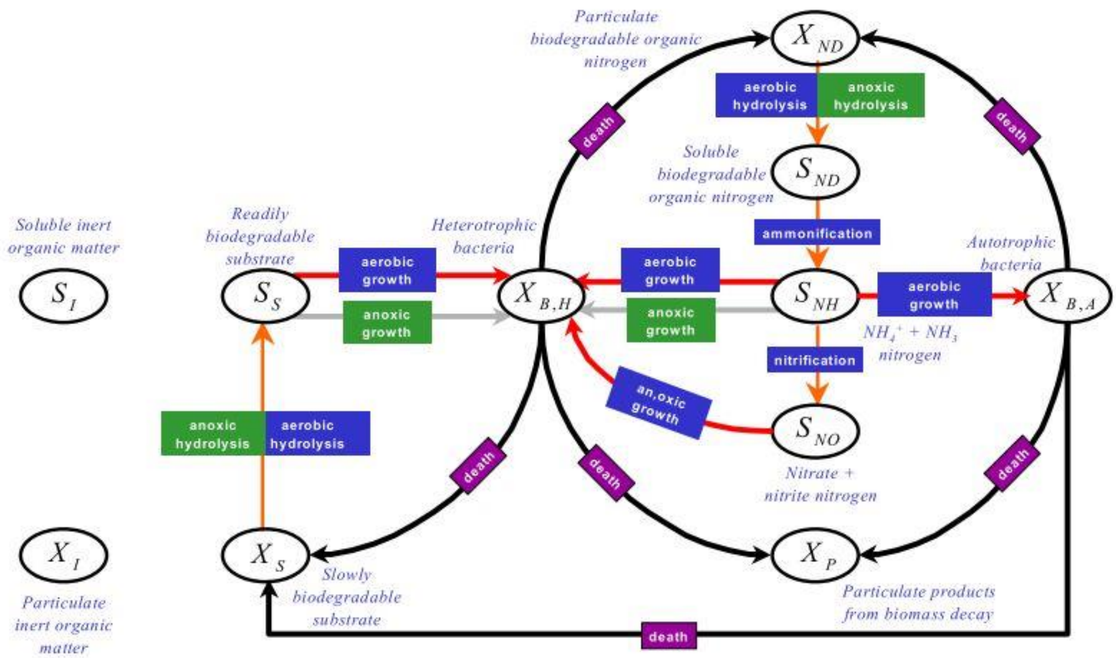


Fig. 4. Scheme of the ASM1 model [116]

The model can be implemented in several specific software: Bio Win™, EFOR™, FORTRAN, GPS-X™, MATLAB™ & Simulink™, SIMBA®, STOAT™ or WEST® [108].

3. 3. ADM1 (Anaerobic Digestion Model No.1)

The International Water Association (IWA) set up the "Anaerobic Digestion Modeling Working Group" in 1997 to build on the need for a generalization of the anaerobic digestion model to go beyond the previously developed models. The ADM1 model was published in 2002 and is the most comprehensive model for the anaerobic fermentation process and serves as the basis for the future development of other kinetic models. However, the complex structure of the model requires improvements, such as interactions between anaerobic microorganisms or the inclusion of aromatic compounds. The complexity of ADM1, which needs many input parameters, however, makes its implementation difficult [117].

The ADM1 model (Anaerobic Digestion Model No.1) is based on 7 groups of microorganisms, and describes the kinetics of 19 biochemical processes, 3 gas-liquid transfer processes and 6 acid-base processes. The model uses 26 concentrations - dynamic state variable variables. In a system of 35 differential equations and 8 algebraic equations, the model describes the reactor behavior of all 35 dynamic state variable variables by means of several kinetic and stoichiometric constants.

Complex reactions in anaerobic fermenters can be divided into two main types.

(a) Biochemical (irreversible) reactions: The ADM1 model includes the three intracellular biological steps (Acidogenesis, Acetogenesis and Methanogenesis) as well as the extracellular disintegration (Hydrolysis) as in the figure:

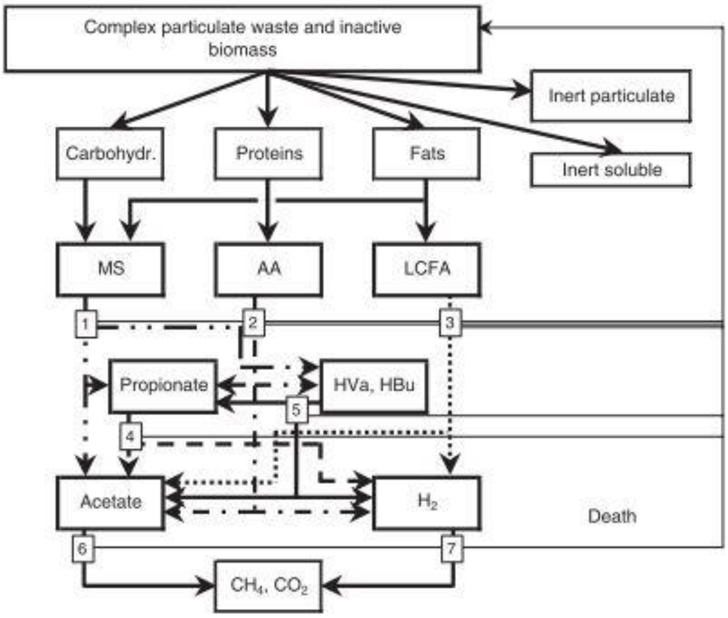


Fig. 5. Scheme of anaerobic fermentation and biochemical processes [105]

(1) Acidogenesis of monosaccharides (MS); (2) Acidogenesis of amino acids (AA); (3) LCFA acetogenesis; (4) Acetogenesis in propionate; (5) Acetogenesis of valerate and butyrate; (6) Mehtanogenesis of acetates; (7) Hydrogenotrophic methanogenesis.

(b) Physicochemical reactions (reversible)

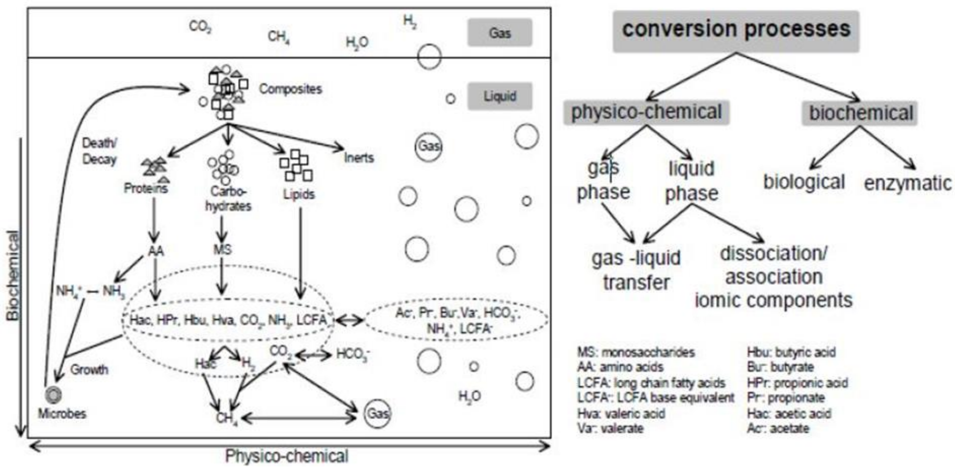


Fig. 6. Scheme of anaerobic fermentation and physicochemical processes [105]

3. 4. ASM1+ADM1

The scientific community has developed a new standardization (BSM2-2007). This includes both the biological treatment of water and sludge treatment processes: thickening of the primary and active sludge in excess, anaerobic fermentation of the sludge and mechanical dehydration of fermented sludge. With this tool various control strategies applied at the level of the entire treatment plant can be evaluated [119]. The scheme of the BSM2 installation is shown in the figure below:

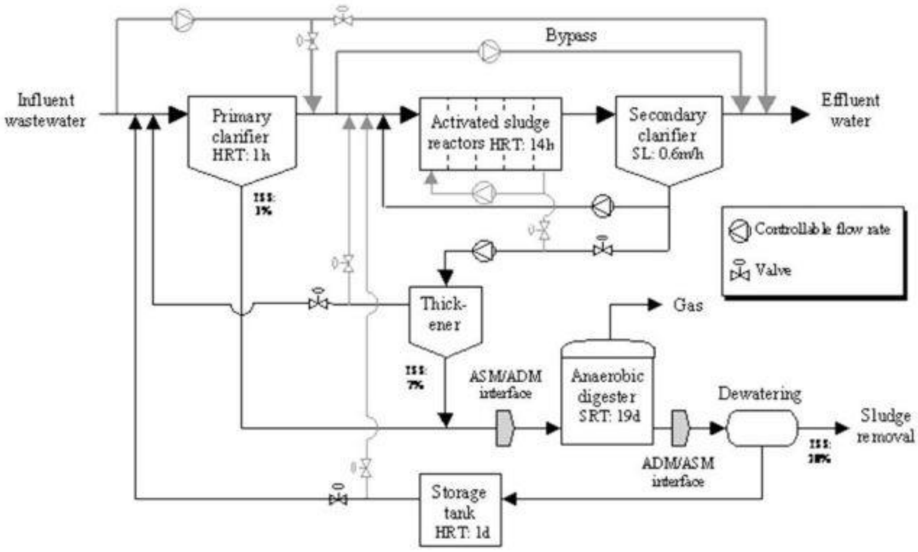


Fig. 7. Scheme of a BSM2 treatment plant [120]

The new BSM2 standardization allows the implementation of long-term control strategies at the entire WWTP including interactions between sub-processes, recognizes the importance of sludge processes, avoids sub-optimization of processes and adds additional elements to seasonal effects on influential flows. BSM2 *incorporates BSM1 standardization for the biological water treatment reactor (a biological reactor described by the mathematical model ASM1 coupled to a secondary decanter described with the Takács model).*

Interfaces have been developed for the primary and secondary sludge sedimentation processes and fermentation sludge dehydration processes. The ADM1 / ASM1 interface is reversible at the ASM1 / ADM1 interface.

The ASM-ADM interface is represented in the following figure:

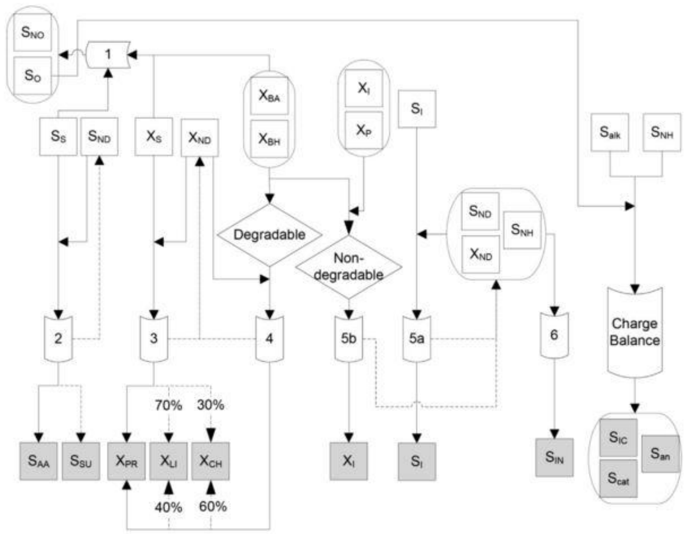


Fig. 8. The ASM - ADM interface [123] according to [119]

The ADM-ASM interface is represented in the following figure:

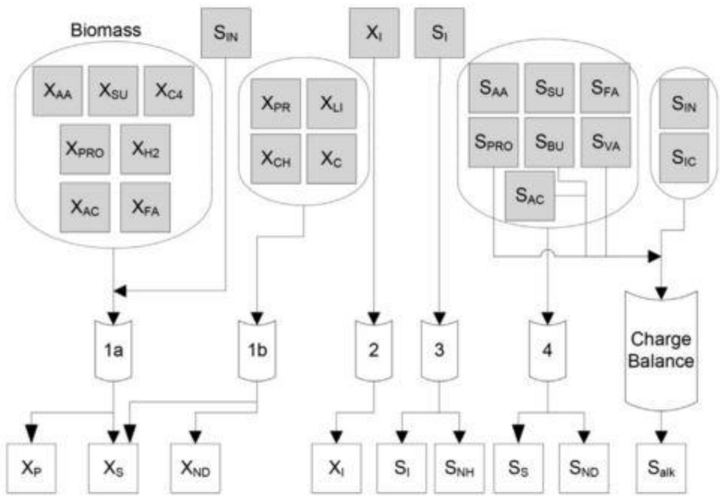


Fig. 9. The ADM – ASM interface [123] according to [119]

Chapter 4. Implementation of the ASM1 mathematical model for the water treatment line

4.1. Takács model of the secondary clarifier

The IWA community proposed in 2002 to define BSM1 the use of the Takács mathematical model for modeling sedimentation processes in secondary clarifier, since separation of suspended solids into water is accomplished by gravitational sedimentation in secondary decanters. [108] Liquid-solid physical separation involves two processes: fluid clarification and thickening of the sludge. Takács proposes in 1991 the use of a one-dimensional decanter divided into 10 hypothetical layers of equal thickness. The model uses the concept of solid flow that disturbs sedimentation and flocculation conditions in the secondary clarifier. An exponential double speed function is used to describe the sedimentation velocity of the various solid components in the mixture. To estimate the solids concentration in the decanter, a mass balance is performed on each hypothetical layer of the decanter.

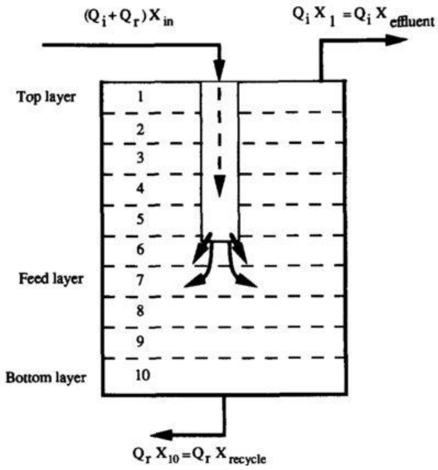


Fig. 10. Takács secondary clarifier model in layers [104]

4.2. Aspects of benchmarking BSM1

The reference plant in BSM1 is composed of an active sludge reactor with five compartments: two denitrification and three aeration. The activated sludge reactor is connected to a secondary decanter. The installation is designed for a dry average flow rate of 18,446 m^3 / day, an influent with a COD = 300 mg / l. The volume of the biological reactor and the secondary clarifier are both equal to 6,000 m^3. The hydraulic retention time (in dry weather) is 14.4 hours. The excess active sludge flow is 385 m^3 / day. The age of biomass sludge is about 9 days.

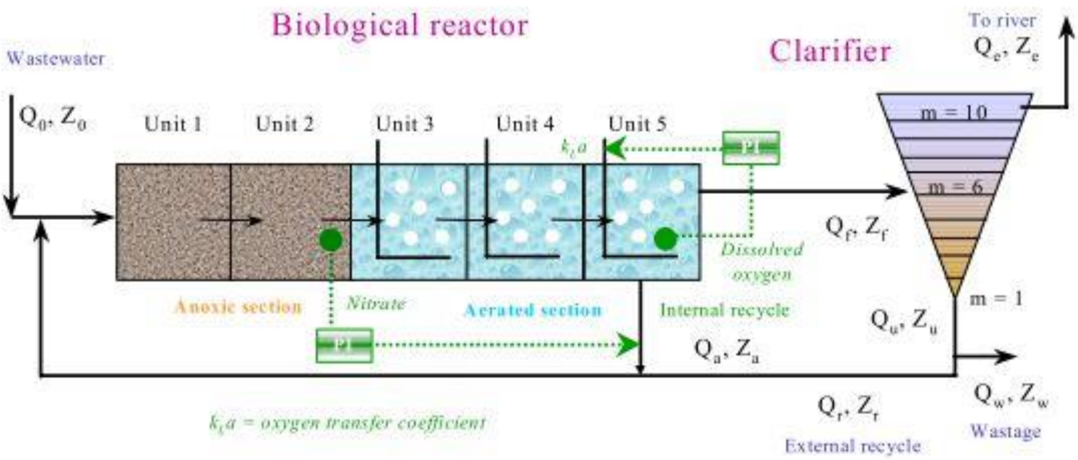


Fig. 11. Scheme of the wastewater treatment process in BSM1 [116]

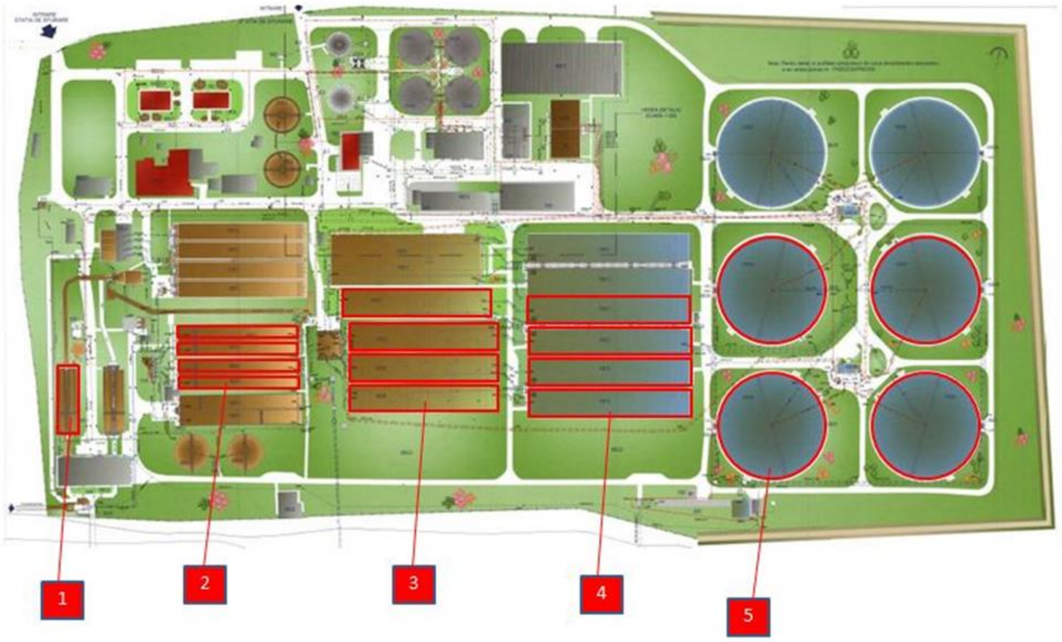
Also, a control strategy is proposed: regulating the dissolved oxygen concentration in the last reactor compartment by controlling the oxygen transfer coefficient and nitrate concentration in the last anoxic tank by adjusting the internal recycle flow [116].

The implementation of an advanced control strategy aims to minimize the energy costs of the sewage treatment plant, as the biological reactor needs about 67% of the electricity required for the entire treatment plant [125], [126].

4.3. Construction details of the wastewater treatment plant. Modeling data

It is desirable to implement the ASM1 mathematical model for a municipal sludge treatment plant with active sludge operating according to an A2 / O scheme. The sewage treatment plant is sized for 367,000 equivalent inhabitants, which processes an average flow of about 110,000 m3 / day of waste water. The equipment of the station is on an area of about 15 hectares. The sewage treatment plant is a new one in which the rehabilitation and expansion works were completed in August 2013. About 33 million euros were invested, of which 74% were European funds. The electricity consumed for the biological treatment of water represents 60-65% of the electricity consumed by the entire treatment plant. Upon completion of the investment, the following environmental quality and water management authorizations were imposed on the discharge into the emissary: total nitrogen = 10 mg / l and total phosphorus = 1 mg / l (with the purpose of limiting emitter phenomena).

After a careful analysis of the operating data, a period considered representative for modeling was chosen: 1 - 22 May 2016. Due to its high capacity, the station is dimensioned with spare equipment in order to limit the risks of environmental pollution. During the model period, the purification plant operated in the following scheme: 2 desulphurization lines, 4 primary decanters, 4 bioreactors (4 denitrification tanks + 4 aeration tanks) and 4 secondary clarifier according to the following figure:



1 = deznisipator ; 2 = decantor primar; 3 = bazin de denitrificare; 4 = bazin de aerare; 5 = decantor secundar

Fig. 12. Waste Treatment Plants Status Plans - Schedule of May 2016

For Mathematical Modeling, a full set of data was obtained from **SCADA** containing a total of 190,081 determinations (at 10-second intervals). For simplicity (through mathematical mediation), the data set was reduced to ***3,128 determinations (at 10-minute intervals)*** and ***22 daily averages***. At the same time, the 22 daily averages provided by the ***wastewater treatment station laboratory*** (RENAR accredited) were analyzed for samples collected with automatic sampling machines.

4.4. Implementing the BSM1 model in Matlab / Simulink.

4.4.1. Implementing the BSM1 model in Matlab / Simulink.

The MATLAB software and the Simulink graphics programming extension are used in the present research. MATLAB along with its Simulink graphic extension

The developed simulator is based on the benchmarking simulation techniques provided by COST Action 682 and the IWA Working Group on Assessment of Control Strategies for Wastewater Treatment Plants [108]. The developed simulator incorporates ASM1. The equations of the 8 bioreactor processes and the secondary clarifier equations are written in the C / C ++ programming language. To reduce simulation time and reserve computing resources, the codes have been compiled and incorporated into the Simulink environment via the S-Function function. For each of the 5 reactors (see Fig. 47), a S-Function file written in the C / C ++ code is made.

Simulink ODE15s has been used to solve the differential and algebraic equations in the model. The following figure shows the structure of the dynamic simulator developed:

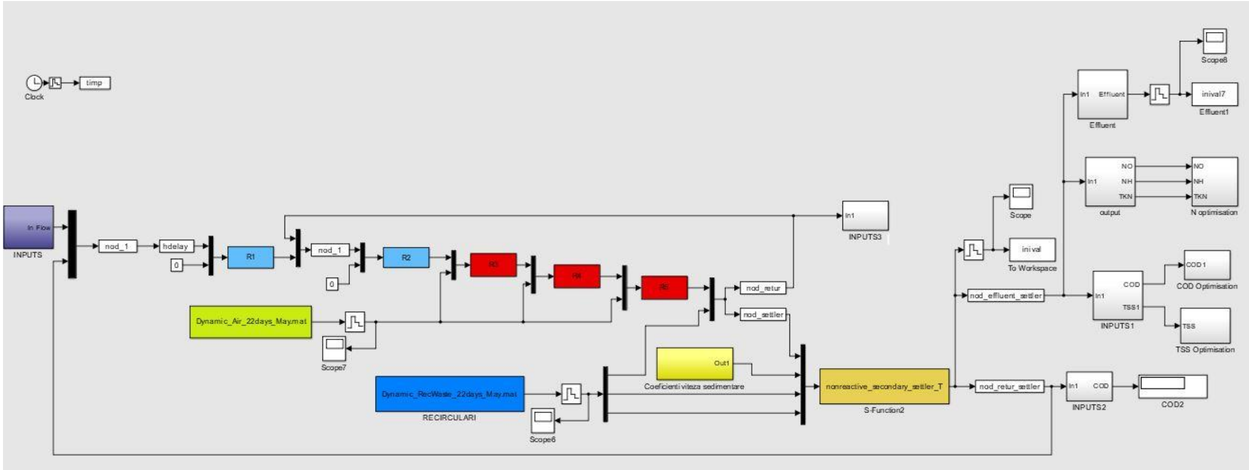


Fig. 13. The Simulator of the Wastewater Treatment Plant built in Simulink

4.4.2. Method of calibration and model optimization

In order to obtain ASM1 model state variables, a new approach has been proposed. It is based on literature, experimental data, and previous simulations. The measured data from the treatment plant studied are relatively limited. It is almost impossible to determine all state variables and ASM1 model parameters by site measurements. Thus, for the influence, concentrations of $X_{B,H}$, $X_{B,A}$, X_P, S_O are considered equal to 0. The remaining concentrations, which are not available, represent unknown inputs of the model. The equations proposed for model calibration are as follows:

$$TSS_{ef} = 0{,}75 \cdot (X_{S,ef} + X_{B,A\,ef} + X_{B,H\,ef} + X_{P,ef} + X_{I,ef}) \tag{4.17}$$

$$COD_{tot,ef} = S_{S,ef} + S_{I,ef} + X_{S,ef} + X_{B,H,ef} + X_{B,A,ef} + X_{P,ef} + X_{I,ef} \tag{4.18}$$

$$COD_{sol,ef} = COD_{tot,ef} - COD_{X,ef} = COD_{tot,ef} - \frac{TSS_{ef}}{0{,}75} \tag{4.19}$$

$$TKN_{ef} = S_{NH,ef} + S_{ND,ef} + X_{ND,ef} + i_{XB} \cdot \left(X_{B,H,ef} + X_{B,A,ef}\right) + i_{XP}(X_{P,ef} + X_{I,ef}) \tag{4.20}$$

$$NO_{ef} = S_{NO,ef} \tag{4.21}$$

$$NH_{ef} = S_{NH,ef} \tag{4.22}$$

$$N_{total,ef} = TKN_{ef} + NO_{ef} \tag{4.23}$$

$$N_{organic,ef} = TKN_{ef} - NH_{ef} \tag{4.24}$$

$$X_{S,inf} = COD_{tot,if} - S_{S,inf} - S_{I,inf} - X_{I,inf} \tag{4.25}$$

$$X_{ND,inf} = TKN_{inf} - S_{NH,if} - S_{ND,if} \tag{4.26}$$

By calibrating the model, the results are as close as possible to those recorded by the treatment plant. In thesis, 7 parameters were chosen: 4 input concentrations (**S_I, S_S, X_I, S_{ND}**) and 3 model parameters of the secondary decanter (**r_p, r_h, f_{ns}**) that were calibrated by optimization.

The optimization method used is based on a classic algorithm based on the fmincon function (abbreviated OC) implemented in Matlab. The fmincon function minimizes the multidimensional objective with restrictions. She identifies the solution, starting from the estimated initial values of the solution. For the classic algorithm it is necessary to provide an initial point for all variables and parameters. Also, the lower and upper boundaries (LB and UB) for optimized variables and parameters have to be defined, based on the study of the literature [132].

Practically, for the 7 parameters chosen, starting from values mentioned in the literature, new values are obtained which bring closer the operation of the simulated wastewater treatment plant. Basically, for each of the 7 parameters a multiplier coefficient will be obtained.

For this, an objective function is defined.

The optimization problem is described in the following equations:

$$min_X obfunc_{total}\ (x_1, x_2, x_3, x_4, x_5, x_6, x_7) \tag{4.27}$$

$$X = [x_1, x_2, x_3, x_4, x_5, x_6, x_7] \tag{4.28}$$

$$obfunc_{total} = obfunc_{COD} + obfunc_N + obfunc_{TSS} \tag{4.29}$$

$$obfunc_{COD} = \left| COD_{ef,industrie} - COD_{ef,model} \right| \tag{4.30}$$

$$obfunc_N = \left|NO_{ef,industrie} - NO_{ef,model}\right| + \left|Norg_{ef,industrie} - Norg_{ef,model}\right| + \left|NH_{ef,industrie} - NH_{ef,model}\right| \tag{4.31}$$

$$obfunc_{TSS} = \left| TSS_{ef,industrie} - TSS_{ef,model} \right| \tag{4.32}$$

$$LB \leq X \leq UB \tag{4.33}$$

Model optimization was performed using the above method. In order to reach steady state, the model ran with constant data for 150 days. The results obtained for the effluent through the mathematical model were compared with the industrial effluent data recorded by the treatment plant. Through the optimization stage, based on the obtained results, the simulator was updated with the calibrated process parameters: **S_I, S_S, X_I, S_{ND}**, respectively the process parameters of the secondary decanter: **r_p, r_h, f_{ns}**.

4.4.3. Results obtained in stationary state

The following results were obtained:

Table 15 Influence concentrations and secondary decanter parameters obtained for stationary state:

Influent component	S_I	S_S	X_I	X_S	S_{ND}	X_{ND}
Concentration [mg/l]	3,72	8,50	6,20	245,75	1,04	6,87

Secondary clarifier parameters	r_h	r_p	f_{ns}
	0,000796 [$m^3/g\ SS^{-1}$]	0,012393 [$m^3/g\ SS^{-1}$]	0,003668

The values obtained with the simulator are comparable to those from the treatment plant and are presented in the following table:

Table 16: Comparison of stationary and industrial simulation results:

Effluent Concentration	Simulator (model)	Wastewater treatment plant (industry)	U.M.
CODsolubile	4,84	4,84	mg/l
TKN	2,00	1,94	mg/l
N_{NH}	0,17	0,17	mg/l
N_{NO}	3,76	3,76	mg/l
$N_{organic}$	1,90	1,77	mg/l
N_{total}	5,76	5,7	mg/l
TSS	12,00	12,00	mg/l

The values of the objective functions and the performance index obtained are:

Table 17: Values of objective functions obtained:

Objective function	$obfunc_{COD}$	$obfunc_N$	$obfunc_{TSS}$	$\boldsymbol{obfunc_{total}}$
Values	<0,01	0,2041	<0,01	**0,2041**

4.4.4. Results obtained in dynamic state:

In order to evaluate the stationary calibration model, dynamic simulations were performed. From the treated treatment plant data are collected at 10-minute intervals. Based on these data, files have been generated for sizes that vary over time. Dynamic simulations were performed for a period of 22 days. As can be seen in the figures below, the calibrated simulator also performs in a dynamic regime relatively close to the measured values at the treatment station. We can say that the chosen calibration method is an efficient one and the built simulator is a qualitative one.

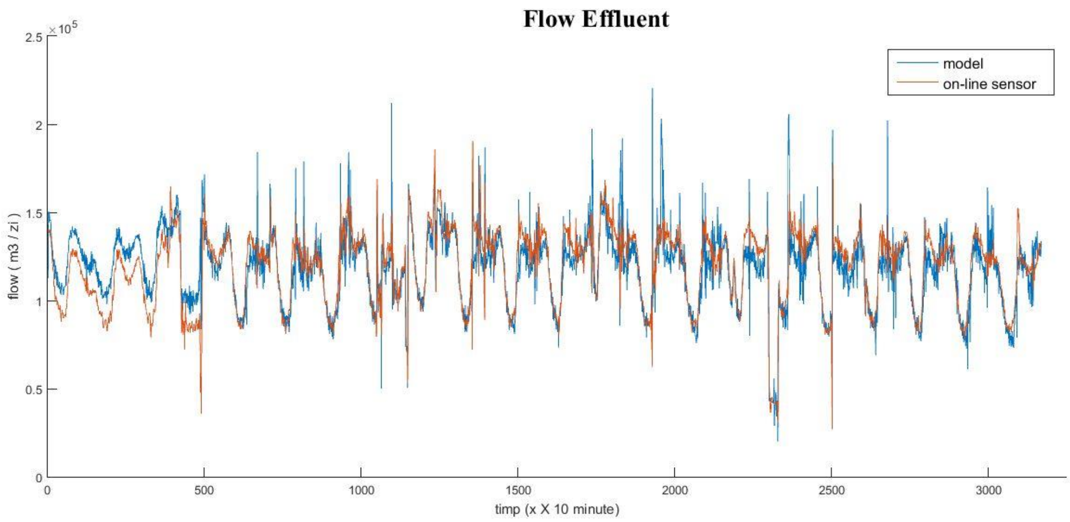


Fig. 14. Simulated results for output flow with dynamic data

For the effluent flow, an average value of 118.311 m^3 / day was obtained for the simulated 22 days, comparable to the 118.766 m^3 / day recorded by the treatment plant (with an error of -0.383%).

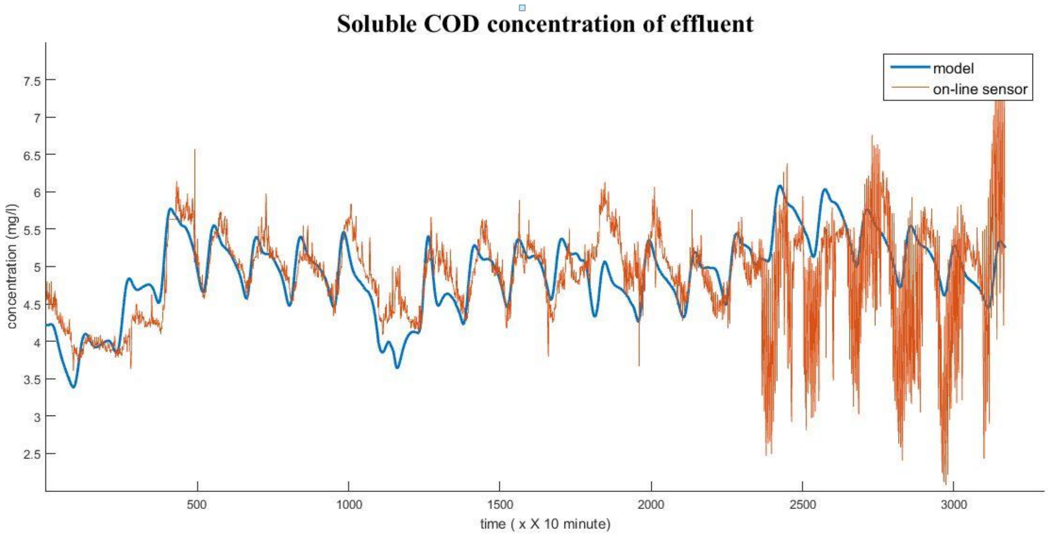


Fig. 15. Simulated results for COD concentration of effluent with dynamic data

For the soluble COD concentration an average value of 5.02 mg / l was obtained. The data obtained were compared to the curve provided by the UVAS probe of the treatment plant. It should be noted that data purchased from day 17 is no longer analytical.

It can be asserted with certainty that the probe records the soluble COD value of the effluent, and the data obtained can be used in the probe calibration in determining a conversion factor. The mathematical model can be applicable to the calibration of the measuring instruments. For the simulated period, *a probe calibration factor of 12,828* was obtained for the first 17 days when the probe provided a qualitative signal at an average value of 64.40 nm.

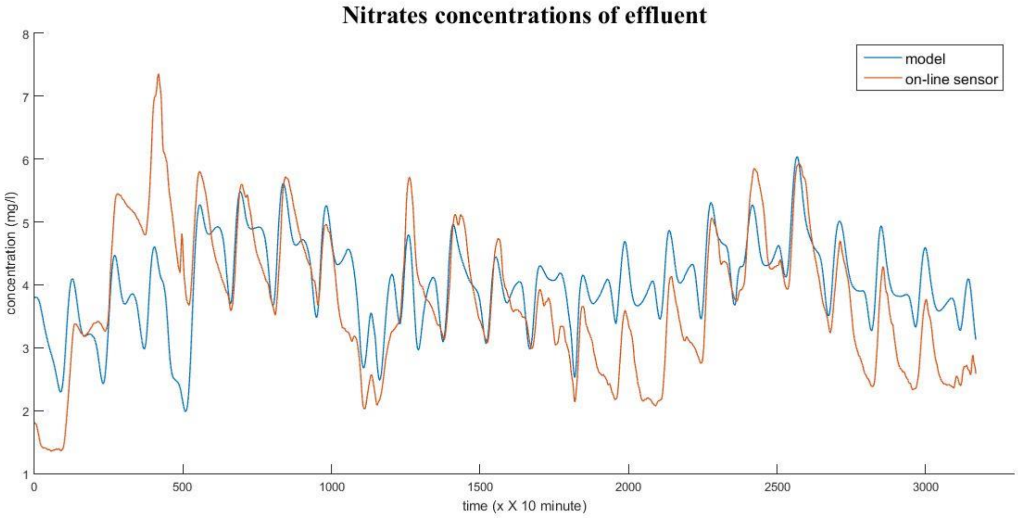


Fig. 16. Simulated results for nitrate concentration of the effluent with dynamic data

The best results were obtained by comparing the results provided by the mathematical model with the results recorded at the nitrate probe treatment station. Thus, for the simulated 22 days, the model provides an average nitrate nitrogen of 3.7498 mg / l, comparable to the average recorded by the on-line probe of 3.76 (with a -0.28 error %). Similar results were also obtained for the total nitrogen concentration of the effluent.

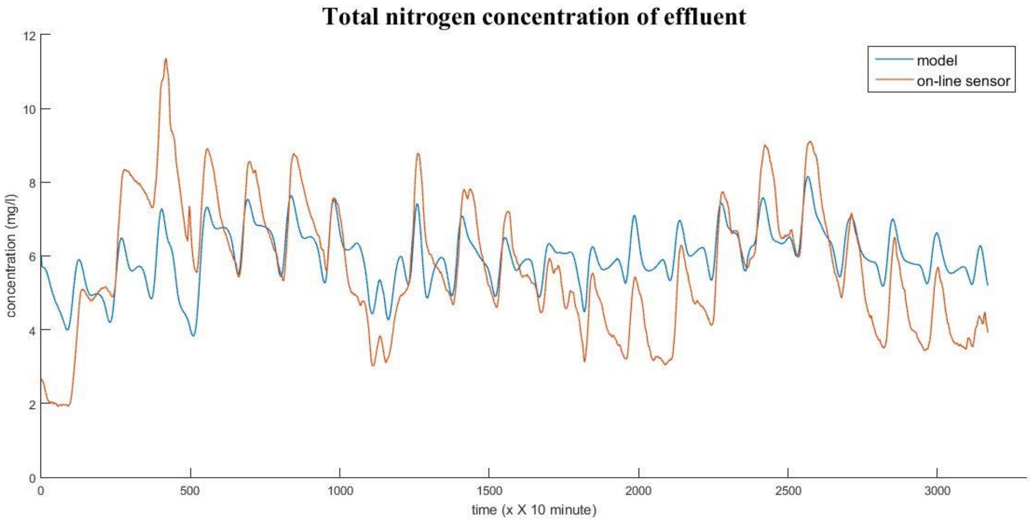


Fig. 17. Simulated results for the total nitrogen concentration of the effluent with dynamic data

For the total nitrogen concentration of the effluent, the simulator obtained a value of 5.68 mg / l, comparable to that recorded by the purification plant of 5.70 mg / l, with a error of - 0.35%.

4.5. Applications of the BSM1 model: 1. Influence of the influent temperature on the biomass treatment composition

The influence of the influent temperature on the biomass composition and the effluent quality indicators is studied. It is known from practice that in the cold season the aeration processes intensify, and in the warm season the cellular activity of the microorganisms intensifies. The question is whether the built model can highlight these aspects.

The model is built and calibrated at an average temperature of 15.83 ° C for the month of May 2016. The temperature data for July 2017 (annual thermal peaks) and February / March 2018 (winter thermal minima) . Thus, for the 22 days of the warm season, the average temperature of the influent is 19.23 ° C and the cold temperature of 12.64 ° C. The three temperature curves are shown in the chart below:

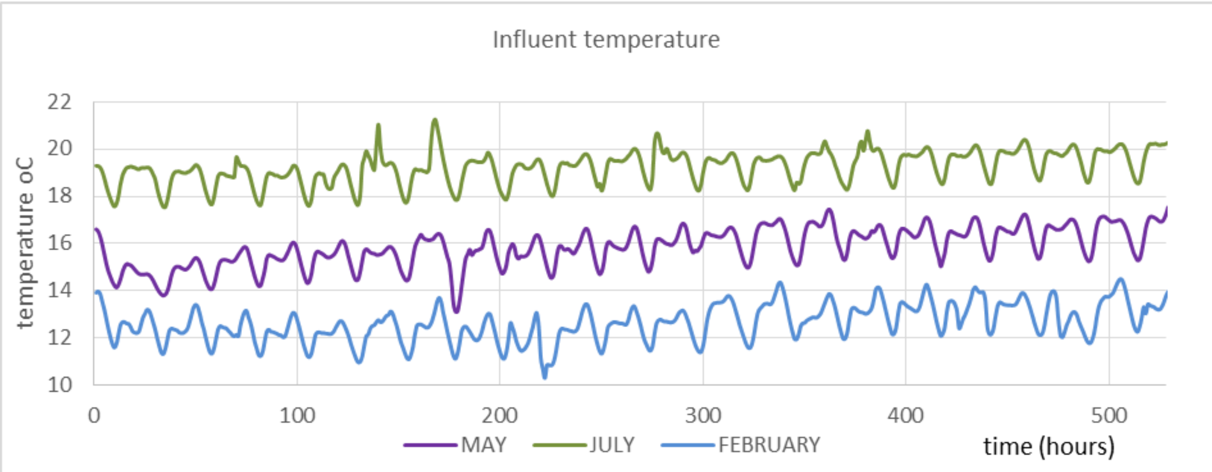


Fig. 18. Time variation of the influent's temperature depending on the season

Two new simulations were run. One in which the temperature curve in the model is replaced by the cold season temperature curve, or in the second simulation with the warm season curve. The results of the simulations are as follows:

In the cold season an inhibition of autotrophic biomass in the denitrification reactor (2) decreases the concentration of autotrophic active biomass (XB, A) from an average of 136.66 mg / l in May to an average of 131.97 mg /it. There is a 3.43% reduction in the active biomass concentration of the autotrophic nitrogen removal reactor.

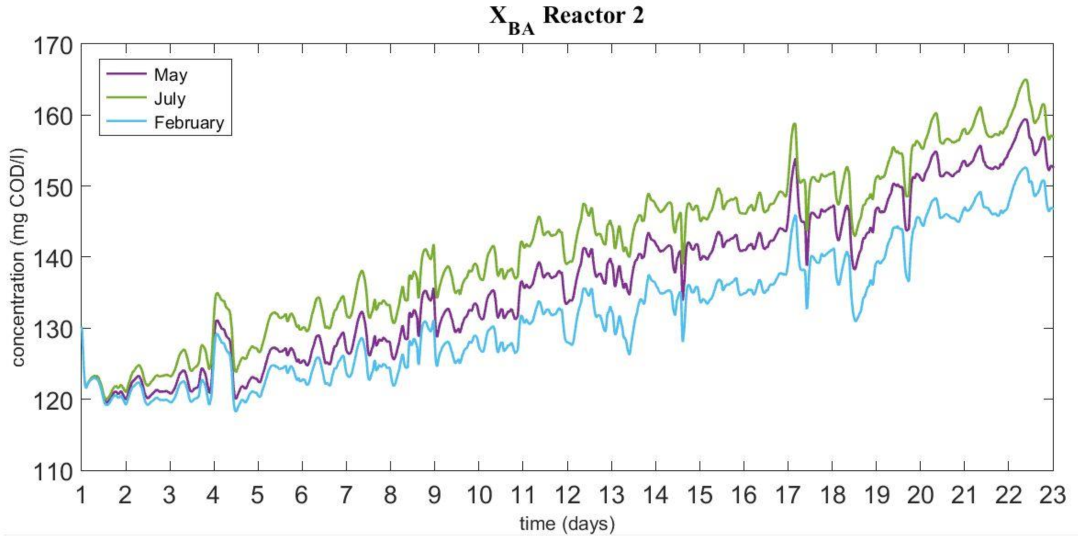


Fig. 19. The time variation of autotrophic biomass in the anaerobic reactor (denitrification)

Decreasing autotrophic biomass concentration takes place up to the last aeration reactor (5), from an average concentration of 137.83 mg / l in May to an average of 133.1 mg / l in the cold season. There is a 3.42% decrease in autotrophic active biomass concentration.

In the five reactors the 3.19 ° decrease in the influence of the influent results in a 3.46% reduction of the autotrophic active biomass ($X_{B,A}$) concentration in the whole system. Increasing the temperature of the influent by 3.4 ° C causes an increase of 3.35% of the total autotrophic active biomass ($X_{B,A}$) concentration in the whole system.

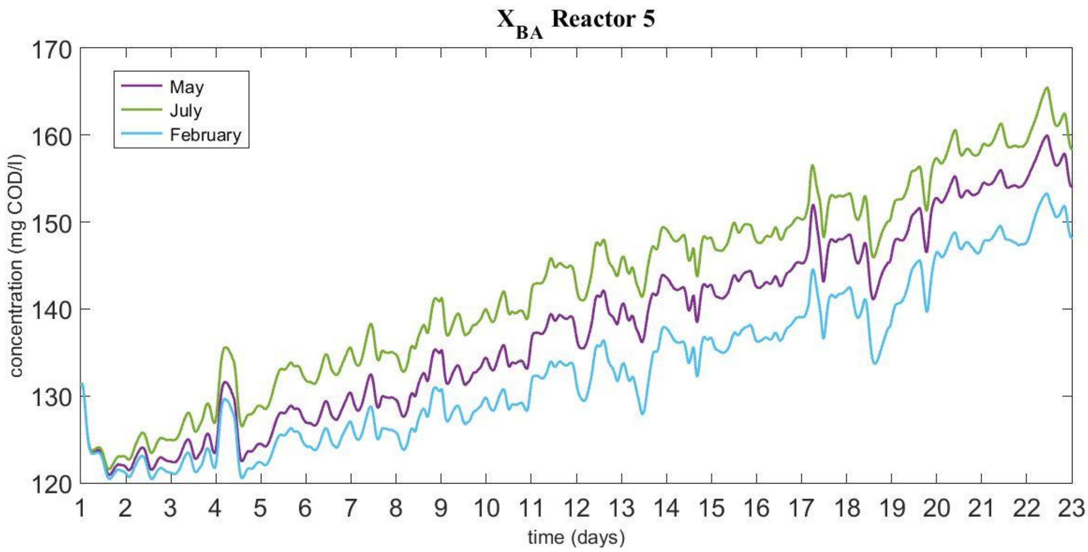


Fig. 20. Time variation of autotrophic biomass from aeration reactor 5 (final part)

Increasing oxygen concentration dissolved in the aeration reactor during the cold season causes an increase in the active heterotrophic biomass ($X_{B,H}$)) concentration from an average of 2265 mg / l in May to an average of 2540 mg / l in the cold month. In the warm season there is a decrease to an average concentration of 1946 mg / l. In practice, in the warm season, aeration processes are intensified to offset this decline.

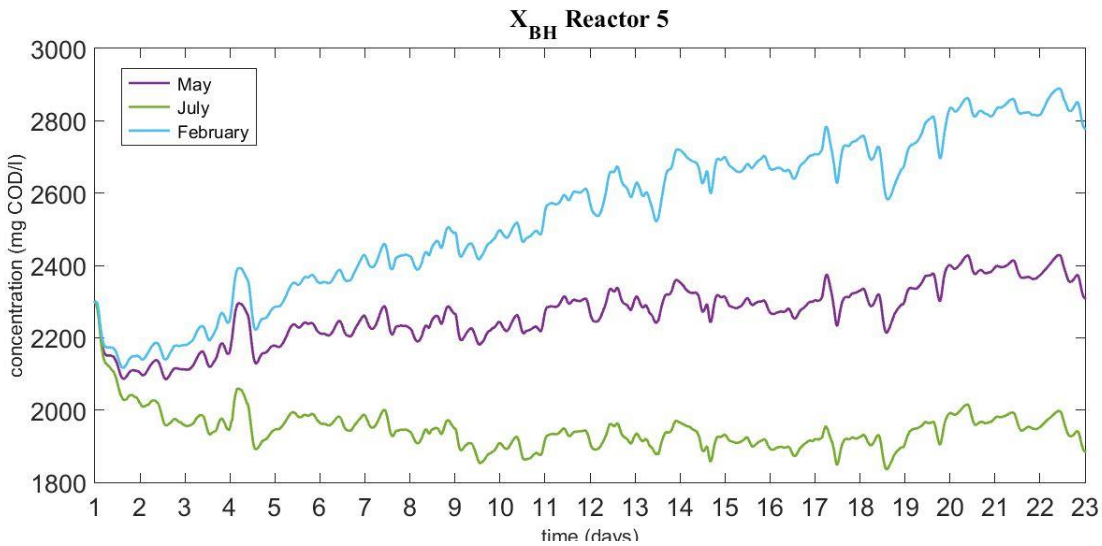


Fig. 21. The time variation of the heterotrophic biomass in the aeration reactor 5 (final part)

Changing the temperature by a ° C causes a 3% change in the active heterotrophic ($X_{B,H}$) concentration of the system, ie a 1% change in the system's active biomass concentration ($X_{B,A}$).

The kinetic parameters determined in the three situations are presented in the following table:

Table 18 Kinetic parameters of the aeration reactor according to the measured temperatures:

Parameter/ Temperature	Symbol	12,68 °C	15,83 °C	19,23 °C	Measuring unit
Heterotrophic growth rate	μ_H	3,4921	4,1957	5,1022	days^{-1}
Rate of autotrophic growth	μ_A	0,3929	0,5442	0,77703	days^{-1}
Ammonification rate	k_a	0,045	0,0519	0,0604	m^3/(g COD day)
Dissolved oxygen concentration at saturation	S_0	8,4086	7,868	7,3656	mg/l
Coefficient of oxygen transfer in liquid	k_La	139,68	150,66	163,32	day^{-1}

It can be observed that intracellular processes responsible for the growth of autotrophic micro-organisms (μ_A) and heterotroph (μ_H) are dependent on the ambient temperature. Also, by increasing the ammonification (k_a)) processes with increasing temperatures, there is also an increase in the concentrations of organic nitrogen that are solubilized. Increasing the ambient temperature causes the dissolved oxygen concentration (S_0) in the reactor to decrease, and the aeration processes become more difficult, more expensive d. Evidence is to increase the oxygen transfer coefficient (k_La) by increasing the temperature.

Although a change of 1% or 3% of the active biomass concentrations in the bioreactor to 1 ° C temperature change in the bioreactor does not seem significant, the following have been noticed: ***decreasing the denitrification processes with the decrease in temperature leads to an increase significant concentration of ammonium nitrogen the effluent (133%).*** The concentration of ammonium nitrogen in the effluent increases from an average of 0.147 mg/l to one of 0.343 mg/l.

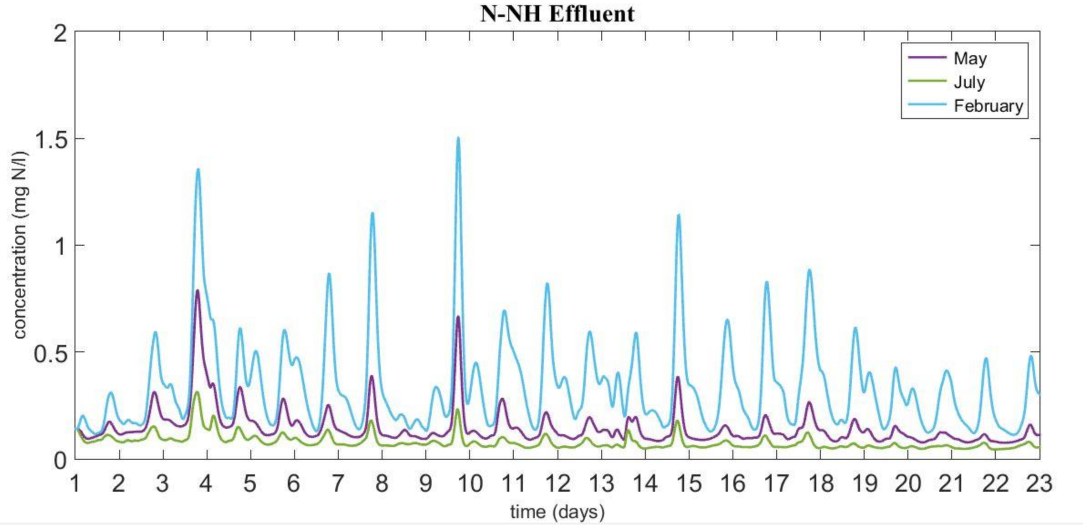


Fig. 22. The time variation of ammonium concentrations in the effluent at different temperatures

Increasing the ammonium nitrogen concentration in the effluent also leads to a significant increase in the nitrogen concentration in the effluent. There is an increase in the mean concentration from 5.68 mg / l to 6.73 mg / l (***an increase of 18.5%***). It is noteworthy that ***in this situation the process approaches the exceeding of the maximum admissible evacuation concentrations*** (ammonium nitrogen= 2 mg / l, total nitrogen = 10 mg / l).

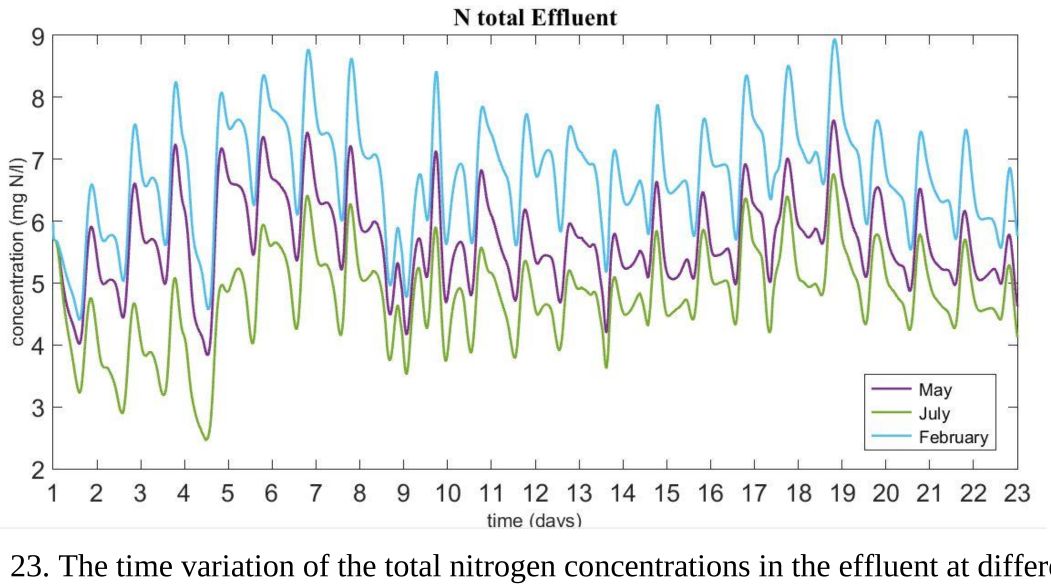


Fig. 23. The time variation of the total nitrogen concentrations in the effluent at different temperatures

4.6. Applications of the BSM1 model: 2. Influence of an external carbon source on water quality parameters. Optimization of denitrification

Due to the decline in the food industry, wastewater becomes more diluted, less loaded into organic carbon compounds. In this situation the concentration of nitrogen present in the wastewater becomes much higher than that required for a balanced development of the bacterial mass. It is recommended that the nutrient ratio in the influent be CBO5: N: P = 90 ÷ 150: 5: 1 [34].

It investigates how an external carbon source, which brings corrections to the nutrient (C: N: P) ratio of the influent, can improve the effluent discharge parameters. According to the literature, in the case of a low C / N ratio, it is recommended to use an external carbon source ***to optimize denitrification***. The following chemical substances are recommended as an external source of carbon: methanol, ethanol or acetates. To obtain results, the external carbon source has to be characterized by a COD / N> 5 ratio [33].

During the simulated period, in 16 of the simulated 22 days, a 10 m^3 van discharges at 8, 12, 18 and 23 hours of sewage used in the dairy industry. Practically, about 40 m^3 of waste water from the dairy industry was received. Analyzing the content of these waters, they comply with the above requirement and can be defined as an external carbon source according to the chemical analyzes performed:

Parameter	pH	COD (mg/l)	NH_4 (mg/l)	NO_3 (mg/l)	N_{total} (mg/l)	P_{total} (mg/l)
Value	5,93	82.874	675	43	2.450	540

Using the mathematical model we want to determine the contribution of these waters to the optimization of denitrification. Three new simulations are running. One is where the external carbon source is added. In this case, the following questions are asked: what was the influence of the external carbon source on the effluent quality indicators? To what extent do the denitrification parameters improve? In the second and third simulations, the external carbon source is introduced at certain time intervals. The first hourly interval is from 5 am to 9 am, the interval corresponding to a minimum hourly flow rate with minimum concentrations of pollutants. The second hourly interval is from 11 am to 3 pm, range corresponding to a maximum hourly flow rate with maximum concentrations of pollutants. The following question arises: In which scenario the external carbon input brings maximum benefits to the process? It is marked with

- **A** scenario with external carbon source introduced according to the data provided by the station;
- **B**-scenario with external carbon source introduced in the range 5 °° - 9 °°;
- **C**-scenario with external carbon source introduced in the range 11 ° - 15 °°;
- **D**-scenario without external carbon source;

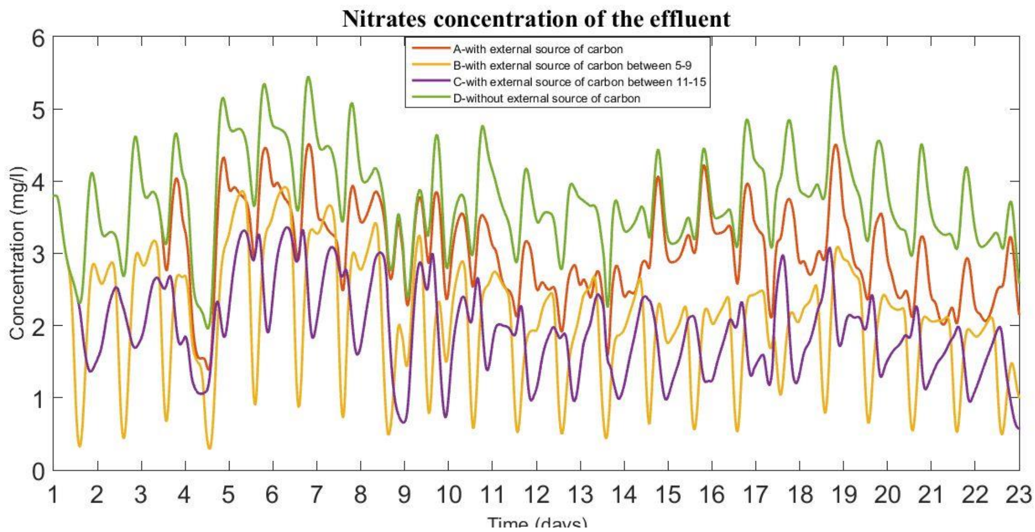


Fig. 24. Time variation of nitrate concentration in the effluent in different dosing scenarios of C

By introducing the external carbon source at the sewage treatment plant at 8°°,12°°,18°°,23°°, the nitrate nitrogen concentration in the effluent was reduced by 17.87 per cent as a result of the optimization of the denitrification. But the process can be further improved. Bringing carbon in between 5°° -9°° can bring a 44% reduction in nitrate concentration in the effluent. The external carbon source brings the greatest benefit to the denitrification process in the scenario in which it is introduced in the 11 ° -15 °° hour range, at the peak flow and pollutant concentration of the influent. In this case, the nitrate nitrogen concentration in the effluent drops by 47.47%. Analyzing the total nitrogen concentrations in the influent we observe that, the process can be improved by introducing the external carbon source between 5°° -9°° (when a pollutant concentration drop is 25.18%) or between 11°° - 15°° (when a decrease in pollutant concentration is observed by 25.88%). Purification can be carried out to achieve a total effluent nitrogen concentration of 4.12 mg / l.

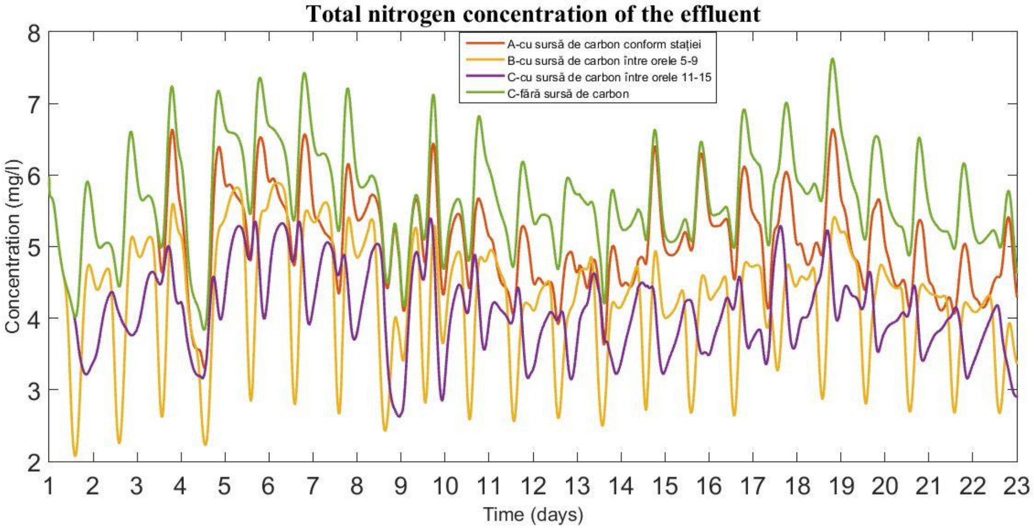


Fig. 25. Time variation of total nitrogen in effluent concentrations in different scenarios

In conclusion, the mathematical model (simulator) has shown that it is reliable to introduce an external carbon source in order to optimize the denitrification process. The best results were obtained at the introduction of carbon intakes at times when the influent had flow and maximum concentration of pollutants.

In detail, we note that the optimization of denitrification by the input of an external carbon source is based on a significant increase in the heterotrophic organisms in the aeration basin and not in the autotrophic processes in the denitrification basin. Thus, providing a surplus of food, bringing corrections to the C: N: P ratio, develops a heterotrophic mass. These heterotrophic microorganisms (optionally anaerobic) under stress conditions (in the absence of air) will decompose higher amounts of nitrite and nitrates into the denitrification reactor (2). The two charts below argue:

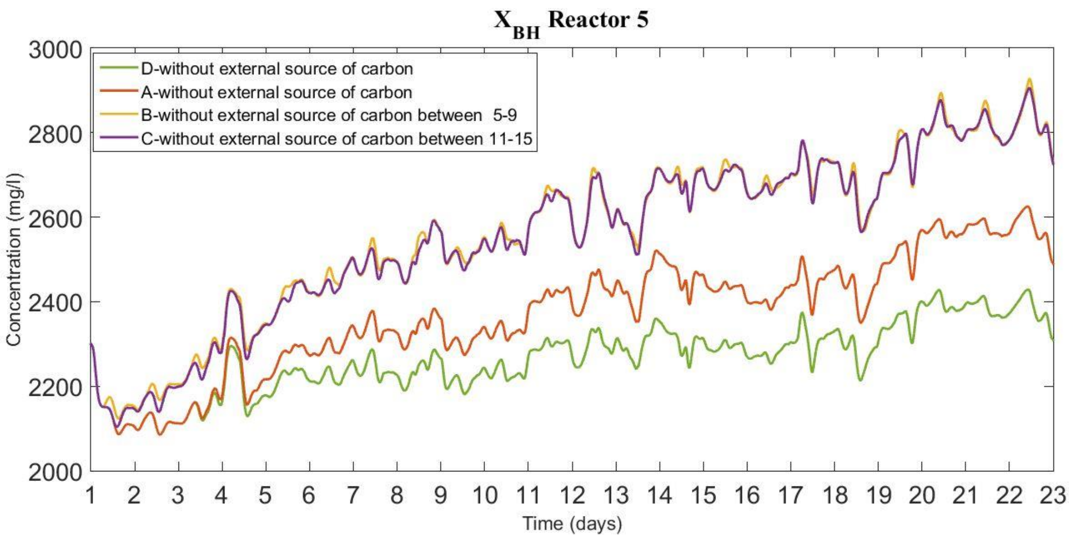


Fig. 26. Time variation of heterotrophic biomass in the aeration reactor in various dosing scenarios of external C

The introduction of the carbon source between 11°°-15°° may provide a 12.92% increase in the concentration of heterotrophic organisms in the aeration basin.

The optimization of denitrification by introducing food for external microorganisms has the effect of lowering the dissolved oxygen concentrations in the aeration reactor by 22.4%.

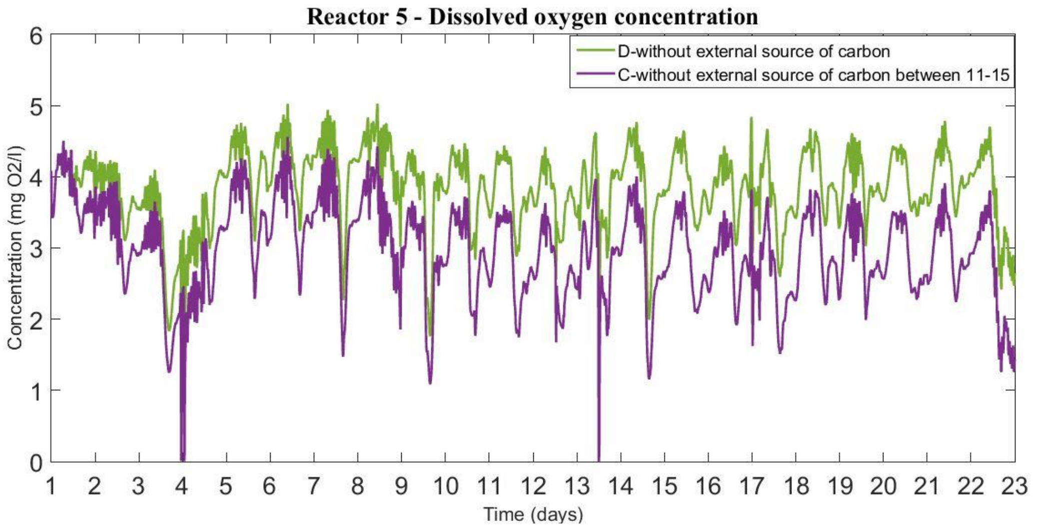


Fig. 27 The variation in time of the dissolved oxygen concentration in the bioreactor with / without external source of C

Optimizing denitrification also leads to optimization of aeration by lowering the oxygen transfer rate in the liquid (k_La). Aeration thus becomes more efficient. Introducing the carbon source between 11-15 hours has the same effect as the 3°C decrease in the bioreactor temperature.

Given that the biological reactor needs about 67% of the electricity required by the entire treatment plant, the optimization of the aeration process results in a reduction in the energy costs of the treatment plant. The simulation results are presented in the following table:

Table 23 Biological reactor parameters in different external source dosing scenarios

Daily average of the 22 days				
Reactor no.2	**A**	**B**	**C**	**D**
X_{BA} (mg/l)	135.55	132.75	132.83	136.66
Reactor no.5	**A**	**B**	**C**	**D**
X_{BH} (mg/l)	2371.90	2563.80	2558.40	2265.60
S_O(mg O_2/l)	3.55	2.94	2.98	3.84

In conclusion: The performance of the biological reactor is directly related to the availability of a carbon source. Chemicals such as methyl alcohol, ethyl alcohol, acetic acid or glucose can be sources of external carbon. All external sources of carbon can also be

industrial waste (waste). However, an examination, detailed analysis of each waste prior to recovery / disposal is necessary. No such treatment can be applied to any wastewater treatment plant. Transport or processing costs can make recovery / disposal of waste unfeasible. In such situations, internal carbon sources, rich in COD, must be examined by means of disintegration of sludge (pre-treatment) or pretreatment (fermentation of sewage, fermentation of primary sludge) [138].

The wastewater treatment plant, using the 3.3 tons / day carbon dioxide (COD) from the dairy industry, can optimize its water treatment process by introducing the carbon source flow between 11°°-15°°. The external carbon source leads to a better removal of nitrogen from wastewater, improves the aeration process and reduces the energy costs of operating the entire wastewater treatment plant. An estimated electricity saving of about 106 MWh / month is estimated, about 6,700 € / month (energy consumption gap between one winter month and one summer). By applying a processing fee (26 € / m³) you can additionally get about € 23,000. The cost reduction can thus rise to 29,700 euros / month.

4.7. Applications of the BSM1 model: 3. Management of sludge liquor from centrifugation of fermented sludge. Influence of ammonium loaded streams on water quality parameters

The present thesis also aims to answer a question from the purification plant that provided the data for modeling and simulation: ***"What is the effect of the sludge liquor from the fermentation sludge centrifugation on the process? What is the optimal operating variant: 8 hours / day of centrifuge operation or 24 hours / day?"***.

The sludge fermented in the anaerobic digesters is subsequently subjected to a mechanical treatment (centrifugal dehydration). Following the mechanical dehydration process two components are obtained: dewatered sludge (a waste - code 19.08.05 *Sewage sludge from urban wastewater treatment*) and the rejection water, which will be treated on the wastewater treatment stream. These sludge liquor are characterized by the following chemical parameters:

Table 24 Determined chemical characteristics of sludge liquor (evacuated waters):

Chemical parameter	Concentration
COD	***1295 mg / l***
Total nitrogen	***542,5 mg / l***
Nitrogen from nitrites and nitrates	***0,77 mg / l***
Nitrogen from ammonium	***436,61 mg / l***
Organic Nitrogen	***55,12 mg / l***

These internal waters are concentrated in ammonium nitrogen and total nitrogen. In the context of a nitrogen-rich (carbon-deficient) influence, the question arises as to how this excess nitrogen (this water) influences the process. During the simulated period, approximately 620 m^3 / day of waste water was generated daily. In two of the 22 days the dehydrating machines were stopped (0 m^3 / day) and in the next 3 days the machines operated at a reduced capacity (280 m^3 / day).

Two new simulations were run. One in which the volumes of the sludge liquor are continuously introduced in the 8°° -16°° or another period in which these waters are continuously introduced during the 24 hours.

They are noted with:

- A-scenario with sludge liquor in the interval 8 °°-16 °°;
- B- scenario with sludge liquor in the interval 0 °-24 °°;
- C-scenario without sludge liquor.

Concentrations of the effluent obtained from the simulations are centralized in the following table:

Table 25 Concentrations of effluent in various rejection water dosing scenarios:

Media zilnică a celor 22 de zile			
Efluent	**A**	**B**	**B**
COD total (mg/l)	19.02	19.01	18.80
COD solubil (mg/l)	5.09	5.09	5.02
Azot total (mg/l)	5.99	5.96	5.68
Azot in azotați (mg/l)	3.99	4.00	3.75
Azot in amoniu (mg/l)	0.19	0.17	0.15

The sludge liquor bring insignificant changes to the COD (Chemical Oxygen Demand) of the effluent:

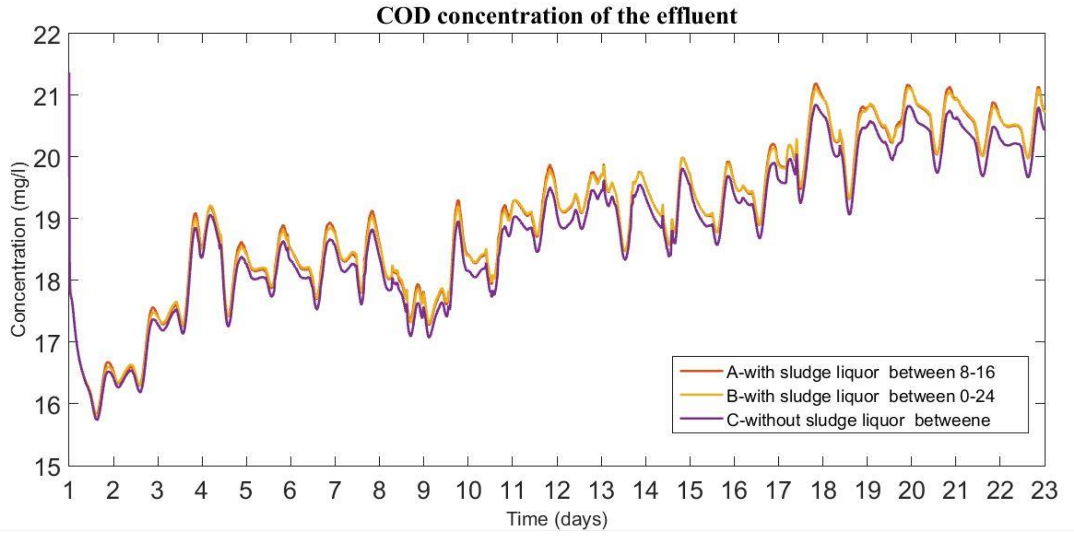


Fig. 28. The time variation of the COD concentration in the effluent in various sludge liquor dosing scenarios

By increasing the amount of nitrogen to be eliminated by introducing these sludge liquor and total nitrogen into the stream, changes in the effluent are as follows:

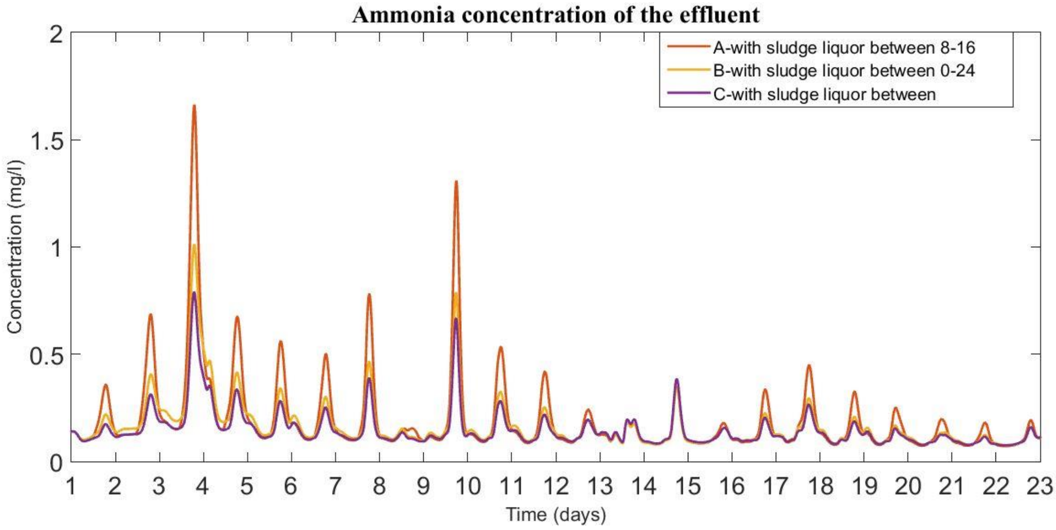


Fig. 29. Time variation of the ammonia concentration of effluent in various sludge liquor dosing scenarios

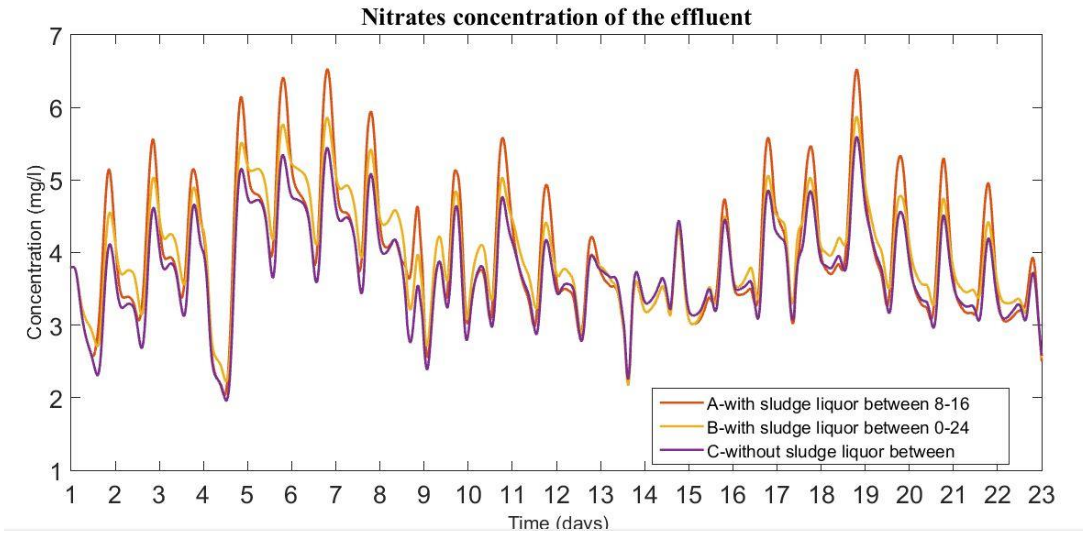


Fig. 30. The time variation of the nitrate concentration from the effluent in various sludge liquor dosing scenarios

Practically the concentrations of all the nitrogen components of the effluent increase. ***So the capacity of the biomass to handle additional amounts of nitrogen is limited. An inhibition of denitrification processes is observed by increasing the nitrate nitrogen concentrations in the effluent. The increase in nitrate concentrations in the effluent causes an increase in the total nitrogen concentration by 5.46% in the case of dehydration of the sludge in the range 8°° -16 °°.***

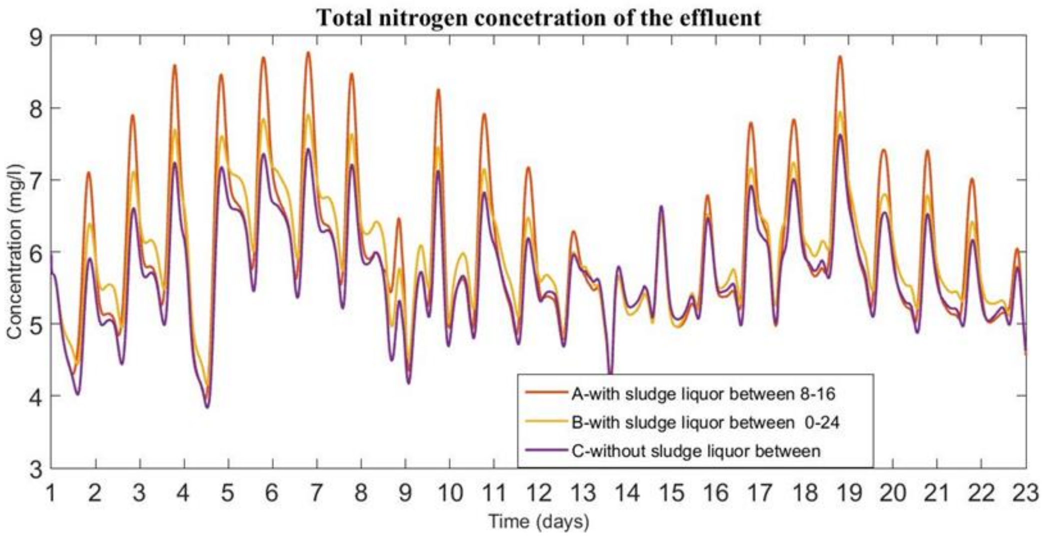


Fig. 31. The time variation of the total nitrogen concentration in the effluent in various sludge liquor dosing scenarios

The feasibility study under which the treatment plant was built provided for the operation of sludge dewatering centrifuges to be 8 hours / day. Such an approach would reduce operating costs, lowering operating staff costs. However, the manufacturer's technical book recommends the use of dehydration centrifuges throughout the day (24 hours / 24 hours). Such an approach, which limits the number of starts / stops of equipment, can reduce the cost of maintenance and repair of equipment, but also increase labor costs.

The answer obtained by simulation is: if a process management is implemented to provide 8 hours / day of dewatering centrifuges, a small increase in total nitrogen (5.46%) in the effluent leads the process (in some moments of time) very close to the maximum (regulated) concentrations. In the event of an additional disturbance, the total nitrogen concentrations in the effluent may be exceeded. The implementation of such an exploitation scheme, with the use of dehydrating centrifuges 8 hours per day, requires complementary implementation of an advanced management strategy.

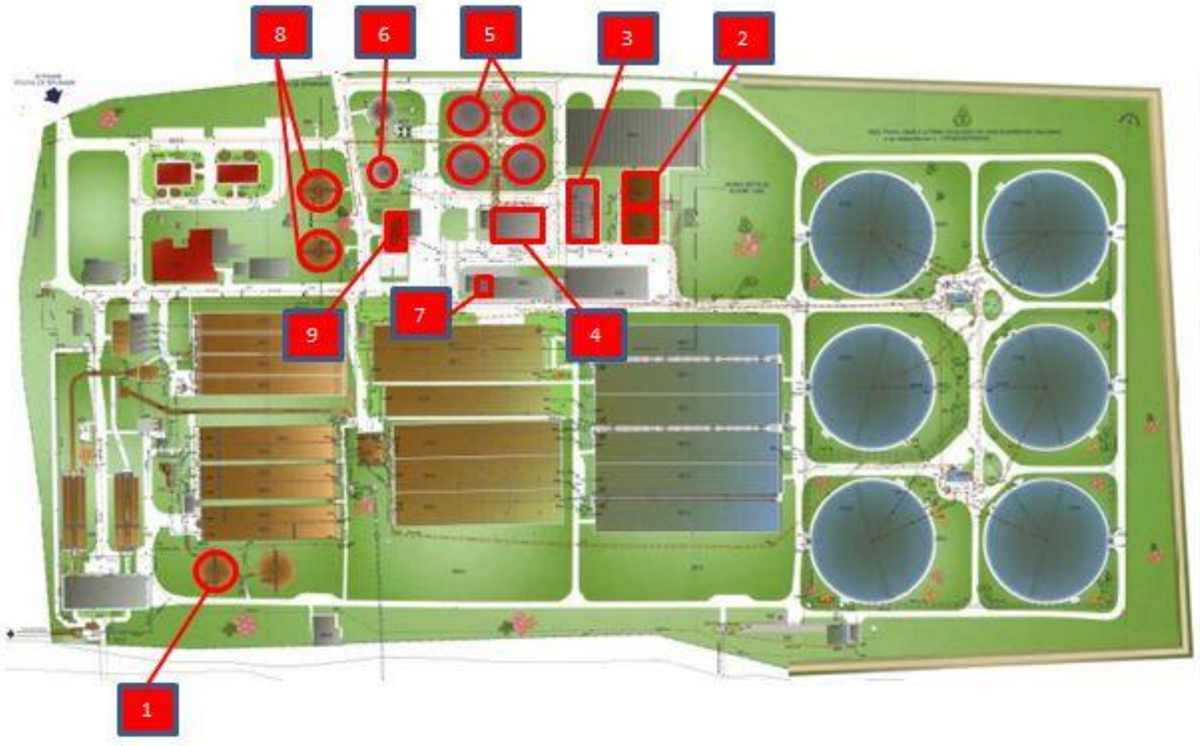
Cost savings in operating 8 hours per day would be about € 1,100 / month (wage costs with 2 employees).

The following should be noted: According to the legislation in force regulating the amount of penalties for exceeding the maximum admissible concentrations of pollutants in waste water, the total nitrogen indicator is paid 7,66 lei / kg of pollutant [137]. In the given situation, where the average flow of influent is very high (119.221 m^3 / day) surplus by one mg / at the total nitrogen concentration at discharge into the emissary, attracts a penalty of 913 lei / day (about 200 € / day) .

Chapter 5. Implementation of the ADM1 mathematical model for the sludge treatment line

5.1. Construction details of the wastewater treatment plant. Modeling data

It is desirable to implement the ADM1 mathematical model for the same municipal sludge treatment plant with active sludge operating according to an A2 / O scheme. Data related to the sludge line operation for the same period for which the water treatment line (1 - May 22, 2016). During the model period, the purification plant operated in the following scheme: 1 primary sludge thickener, 2 excess activated sludge buffer, 4 excessively active sludge mechanical pullers, 4 heat exchangers, 4 mesophilic anaerobic fermentation broths, 1 gas meter , 2 co-generators, 2 fermentation sludge buffer pools and 2 fermentation sludge dewatering centrifuges, according to the following figure:



1= îngroșător de nămol primar; 2= bazine tampon de nămol activ în exces; 3= îngroșătoare mecanice de nămol activ în exces; 4= schimbătoare de căldură; 5=metantancuri de fermentație mezofilă; 6= gazometru; 7= co-generator (CHP); 8= bazine tampon de nămol fermentat; 9=centrifugi de deshidratare nămol fermentat

Fig. 32. Waste Treatment Plant Plan – Operation scheme of May 2016

The sewage treatment plant is well-equipped with control tools for the water treatment line. Sludge treatment is considered to be a secondary one. This is why the measuring and control tools for the sludge treatment line are scarce. We can say that the monitoring and management of the fermentation processes is done according to a basic technique (see fig. 33). No advanced management techniques (predictive algorithms, neural networks or fuzzy logic) are implemented for the sludge treatment line. Process data from existing control tools is acquired in a SCADA system.

For Mathematical Modeling, a full set of data was obtained from SCADA containing a total of 190,081 determinations (at 10-second intervals). For simplicity (through mathematical mediation), the data set was reduced to 3,128 determinations (at 10-minute intervals).

The WWTP consumes about 2,33800 kWh per day and co-generation can provide up to 45% of the energy requirement.

It should be noted that no automatic sampler is provided on the sludge treatment line. In this case all chemical analyzes are performed on samples taken at the moment, with a weekly frequency of determination. In this situation, errors may occur due to evidence considered unrepresentative. Also the station laboratory (RENAR accredited) determines only a limited number of physicochemical indicators for sludge samples.

Thus, for the monitored period, there are 3 sets of physicochemical analyzes provided by the station lab for process flows. The following indicators are determined: sludge humidity (%), volatile content (%), suspension content (mg / l) for the two streams feeding and for the content of the 4 digesters.

The station is equipped with 4 CSTR digesters of 3,500 m3, operated at a temperature of approx. 30-35 ° C, with a HRT retention time = 15-21 days, provided with a sludge recirculation system and mixing.

5.2. Implementation of ADM1 in Matlab / Simulink

The MATLAB software and the Simulink graphics programming extension were used again to develop the simulator. The built simulator is based on the simulation techniques of the IWA working group that developed the ADM1 model [105]. The 35 differential equations and 8 algebraic equations for bioreactors are written in the C / C ++ programming language. To reduce simulation time and reserve computing resources, the codes have been compiled and incorporated into the Simulink environment via the S-Function function. For each of the 4 fermenters a S-Function file is written in the C / C ++ code. Simulink ODE15s has been used to solve the differential and algebraic equations in the model. The following figure shows the structure of the dynamic simulator developed:

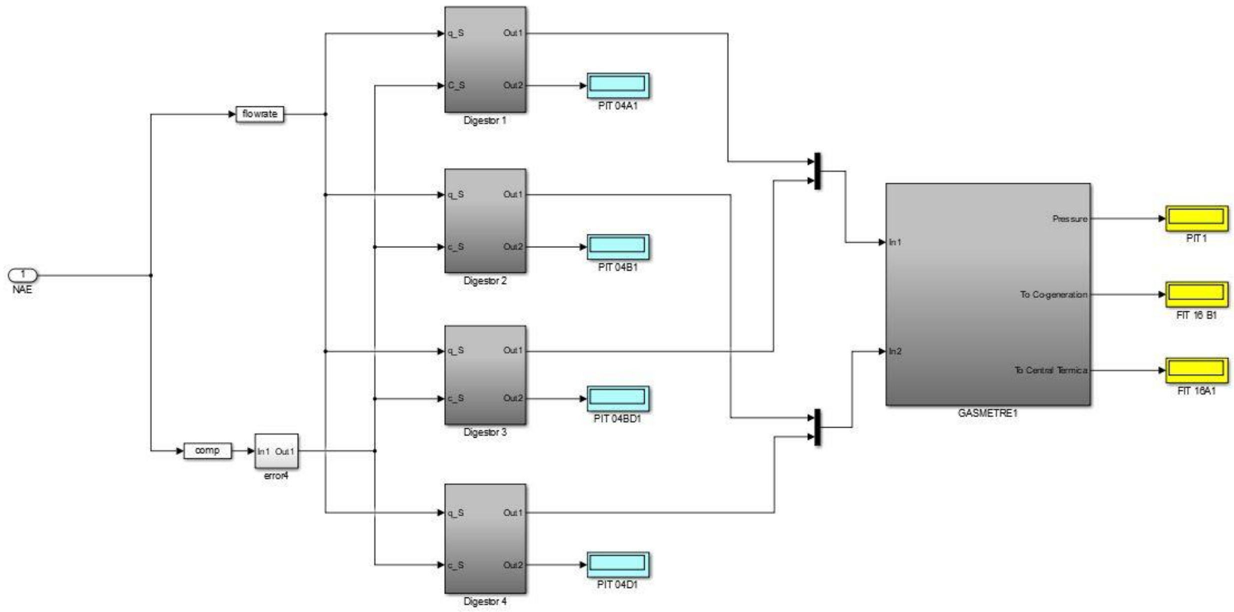


Fig. 33 The sludge line simulator built in Matlab / Simulink

To maintain a constant fermentation temperature, the sludge in the bioreactor is recycled through heat exchangers. Also, 20-25% of the biogas produced is recirculate in the bioreactor to mix the biomass.

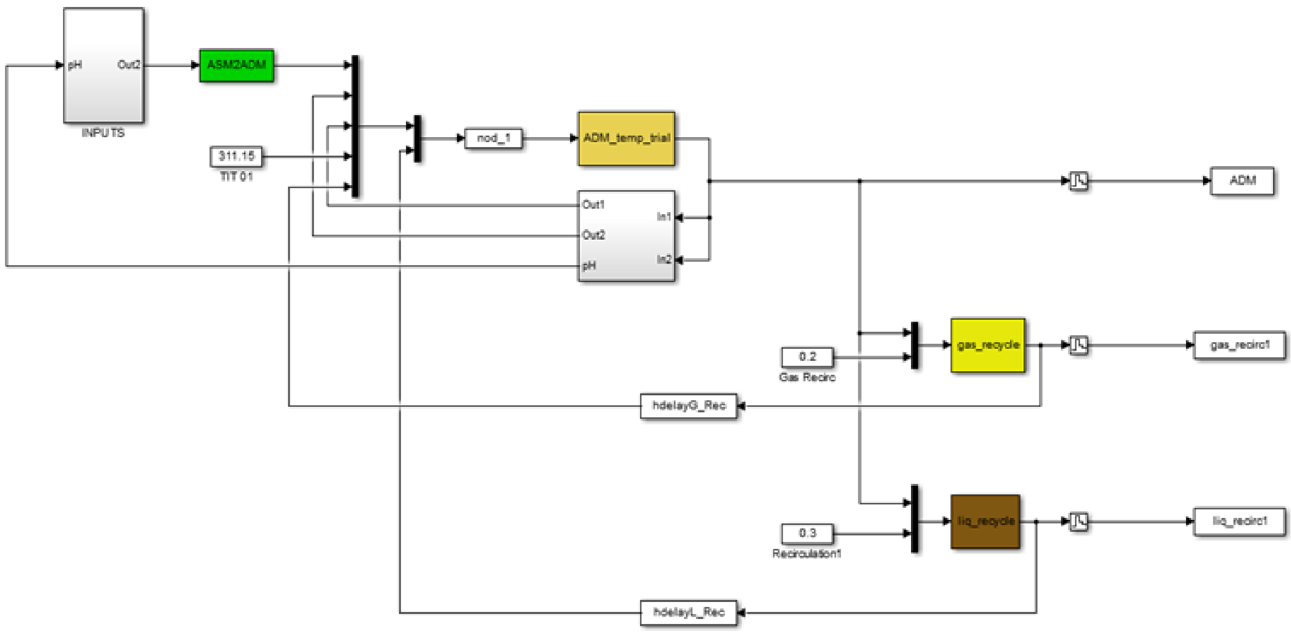


Fig. 34 Scheme of sludge and biogas recirculation in MATLAB/Simulink® [140]

The ADM1 was connected to an ASM-ADM converter that provides a detailed ASM1 parameter conversion algorithm to ADM1. This assures the input variables that are provided from the ASM1 outputs. The ASM1 input variables are less complex and can be more easily determined as compared to the inputs in the ADM1 model. This has resulted in the creation of a simulator for the entire BSM2 benchmarking plant. The simulator of the entire station developed in Matlab has the following form:

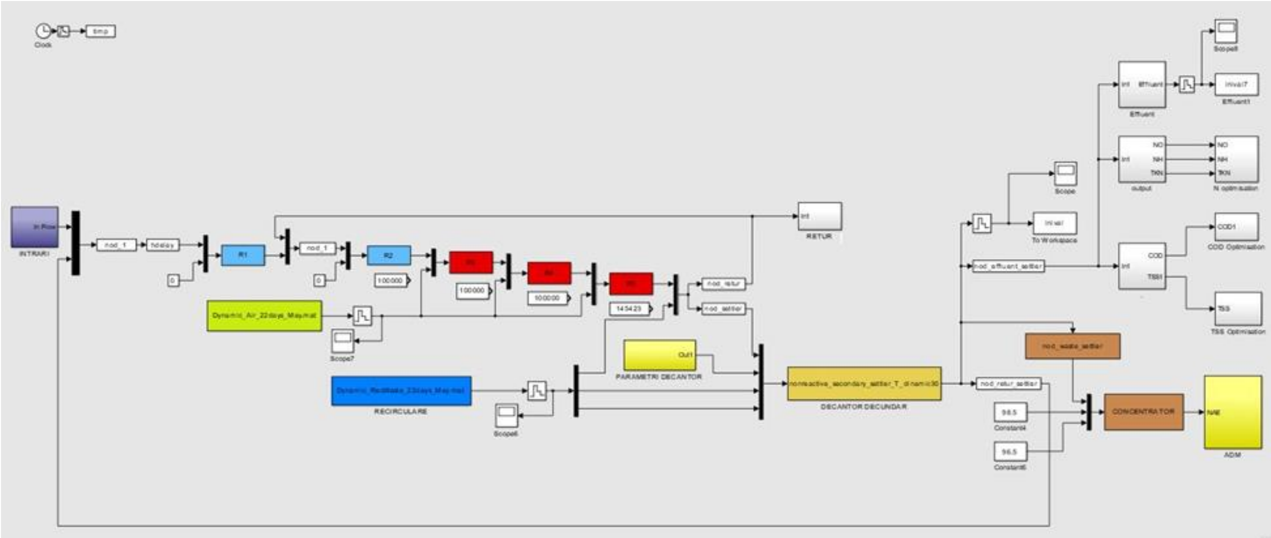


Fig. 35. Simulator of the entire WWTP built in Matlab / Simulink

Even after the implementation of the ASM-ADM interface for the fermenter model, the input variables used are completely different from those that are commonly monitored in the industry. Methods for direct measurement of these input variables (acetic, butyric, propionic, valeric, etc.) are not available. Even if the literature provides values for input parameters, they can not be used directly for an industrial fermenter due to the large variations in the composition of sewage sludge [141]. Using the default values in the literature for the composition of the sludge , or the parameters obtained with the ASM - ADM converter, or the stoichiometric and kinetic parameters presented in the ADM1 model, the mathematical model was not able to obtain results close to those obtained in the pressure purification station fermentation or methane production (on-line monitored sizes in the treatment plant). It is necessary to calibrate the input quantities in order to obtain results close to those obtained in the treatment plant. Further determinations of the composition of the influent are needed, the implementation of new on-line monitoring equipment.

Although the present research has succeeded in interconnecting the ASM1 simulator (for the water treatment line) with ADM1 (sludge fermentation) in order to provide input data for the sludge treatment line model, it was not possible to calibrate the entire ASM1 -ADM1. Process data for sludge fermentation are relatively few. Although the volumes are well known, the composition of fermented sludge is not known. It should be noted that its characteristics are variable over time (humidity, volatile content, etc.). Additional on-line determinations and monitoring are required.

Although the present research has succeeded in interconnecting the ASM1 simulator (for the water treatment line) with ADM1 (sludge fermentation) in order to provide input data for the sludge treatment line model, it was not possible to calibrate the entire ASM1 -ADM1. Process data for sludge fermentation are relatively few. Although the volumes are well known, the composition of fermented sludge is not known. It should be noted that its characteristics are variable over time (humidity, volatile content, etc.). Additional on-line determinations and monitoring are required. Even if the results provided by the model are close to the industrial ones, optimizations should be made to the front model versus the composition and characteristics of the influent sludge of the composite material that is subject to fermentation. Optimizing the terms $\mathbf{f}_{li,xc}$, $\mathbf{N}_{xc}$, $\mathbf{f}_{ch,xc}$, $\mathbf{f}_{pr,xc}$, $\mathbf{f}_{sI,xc}$ to describe the characteristics and composition of the sludge as closely as possible would lead to superior results, implicit in model calibration. On-line monitoring of a small number of output sizes (pressure, biogas flow) makes the terms above impossible to be determined by mathematical simulations.

The results provided by the model are similar to the results of recent studies for the modeling industrial installation [140, 142]. The simulator is able to predict with a 2% biogas feed rate, respectively with a 10% error in the fermentation reactor. The results obtained by simulation match the industrial ones:

Table 26 Simulated results for the industrial wastewater treatment plant:

Output parameter	Mathematical Simulator	Industry
Volume of biogas produced	3,312 m^3 / day	3.000 m^3 / day
Methane concentration in biogas	69,37 %	70 %
Reactor pressure	49,42 mill bars	25 mill bars

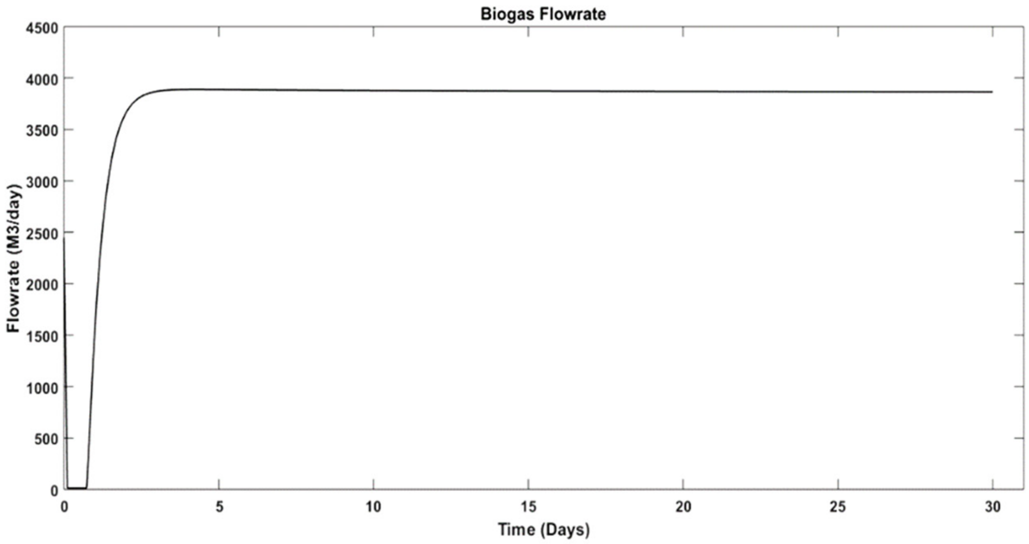


Fig. 36 Biogas Flow rate (m^3 / day) produced in time [140], [142]

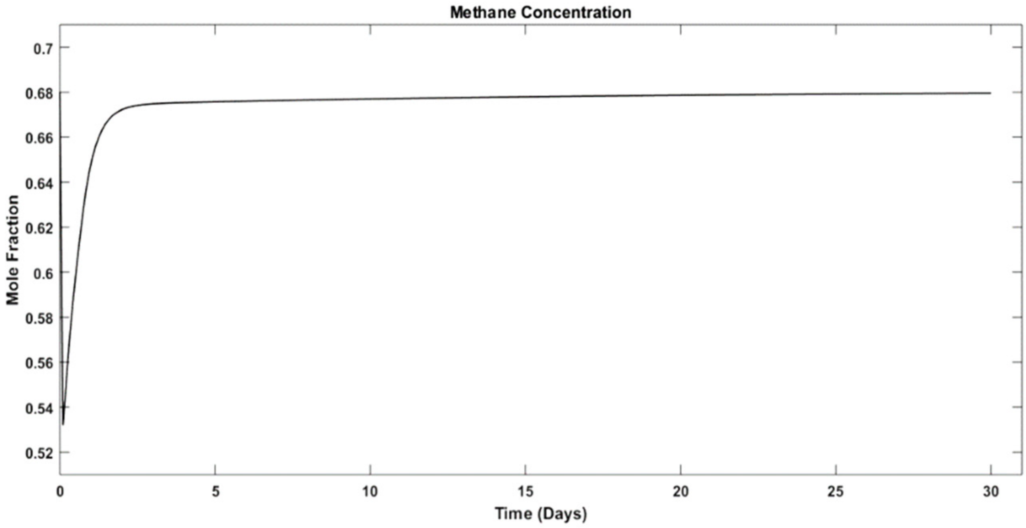


Fig. 37 The time variation in the methane concentration of [140], [142]

5.3. Anaerobic co-fermentation

Anaerobic co-fermentation means the ***simultaneous fermentation of two or more substrates***. Co-fermentation can improve the economic yields of an installation, making it a feasible option to overcome the shortcomings of mono-fermentation. For researchers in the field of anaerobic fermentation, co-fermentation is today the most common subject. If between 1995 and 2005 less than 20 articles on co-fermentation were published annually, now (after 2013) their number exceeds 160 articles annually [15]. Co-fermentation has become a common practice for many WWTPs in Europe. It is estimated that around 216 treatment plants in the USA practice co-fermentation of their own sludge with different organic waste. However, the lack of highly qualified staff in treatment plants makes little information available in the literature [13]. Most of the studies reported are for CSTR-type fermenters in the mesophilic or thermophilic field, highlighting how co-fermentation has improved the process, or how the OLR has grown from the fermenter [15].

Out of the 2.32 billion tons of municipal waste generated in 2017 by the 28 EU member states, only 59.28% were subjected to treatment (recycling, composting, etc.) the remaining 40.72% being stored on the soil [2]. By landfilling, water can be polluted and soil contaminated, the landfill can become a source of pathogens, and methane (greenhouse gas) emissions are significant. In municipal waste management anaerobic fermentation is a better practice. Thus, the solids content can be reduced (> 90%), biogas can be produced, less space / volume is used, and methane emissions are also reduced. Co-fermentation of sludge from sewage sludge (poor biodegradable sludge) along with other organic waste has become an interest and has developed in recent years. Wastewater treatment plants thus become the great beneficiaries of this practice over time.

5.4. Review study on the recovery of waste from the dairy industry by co-fermentation

This thesis aims to answer the following questions:

> What would be the effect of these wastewaters in the dairy industry on anaerobic fermentation in the event they were introduced to the sludge treatment line? Can the sewage plant receive waste from the dairy industry and exploit it by co-fermentation? It is worth mentioning that 3 milk processing plants operate in the county.

In addition to the review study conducted in subchapter 4.6 the following observations are made:

1. Milk consists of water (87.3%) and other components that together make up the dry substance (12.7%). The dry substance contains protein, fat, lactose, mineral substances, etc. The most representative protein is casein (representing about 80% of all milk proteins). Lactose is the main glucose (carbohydrate, sugar) of milk. Lactose is a colorless, odorless crystalline substance with a sweet taste containing between 25 and 60% sucrose. Milk or milk products contain between 1.5-8% of lactose. Cow's milk contains lactose up to 47 g / l of milk. Lactose belongs to the disaccharide category, it consists of a D-galactose molecule and a D-glucose molecule. Lactose, as a component part of milk, is important in feeding young mammals. It plays a role in stimulating digestion by breaking it down by the enzyme lactase into glucose and galactose. Among the functions of lactose it can be remembered that it gives the body energy, stimulates the absorption of calcium [147]. By selective hydrolysis of whey lactose monosaccharaides may be obtained. Under the action of bacteria, lactic, propionic or butyric fermentation takes place. The chemical reactions are as follows:

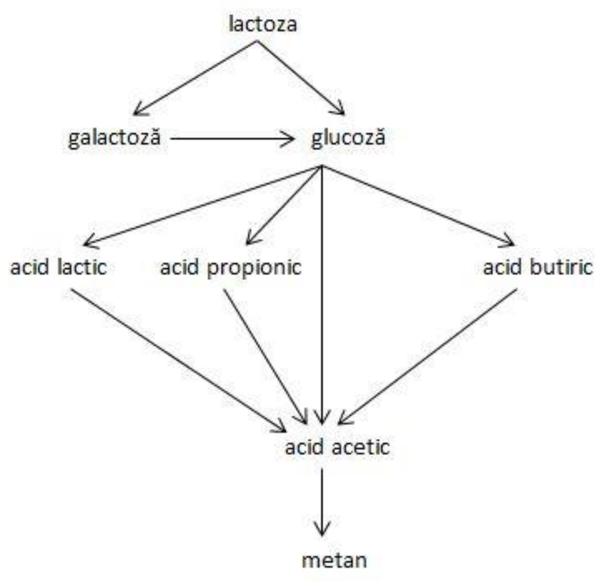


Fig. 38 Mechanism of transformation of lactose into methane [148]

2. The Gloversville-Johnstown, NY, USA wastewater treatment plant co-ferments wastewater from the dairy industry [20], [13], [19]. The station has the capacity of 41,640 m^3 of waste water per day, the total capacity of the fermenters is 10,600 m^3, it produces 6,6 GWh of electric power and 9 GWh of thermal energy annually, being independent of the d. Energy. The plant processes daily 45 to 60 m^3 of whey in the dairy industry.

5.5. Applications of ADM1: The Influence of an External Biodegradable Carbon Source on Biogas Production. Optimizing the process

In the present thesis, it was desired to build and calibrate a simulator for a large urban wastewater treatment plant. Even if it was built, it could not be calibrated on the sludge treatment line. It was also wanted to highlight the positive contribution of an external source of carbon to the water treatment and fermentation biomass. If this has been done for water treatment processes, only the theoretical aspects and industrial examples have been highlighted for sludge treatment processes. Certainly the wastewater (waste) in the dairy industry is an external source of carbon that can correct the nutrient ratio C: N: P for both water purification and sludge fermentation processes. The process simulator should also provide additional information on how to optimize the economic parameters of the sewage plant: either by capitalizing the carbon source on the water treatment line or sludge fermentation.

By introducing the 40 m^3 / day of whey on the water treatment line, additional revenues between 6.700 – 9.000 € / month can be obtained. When the 40 m^3 / day of whey are introduced to the sludge fermentation line, the additional revenue from increased biogas and electricity production can only be estimated theoretically.

Chapter 6. Conclusions and recommendations. Personal contributions

The present thesis brings new elements of mathematical modeling for this treatment plant. The developed simulator provides a first overview of the entire station: the water treatment line as well as the sludge treatment and biogas co-generation. The implementation of the IWA models, of the BSM1 + ADM1 model, brings new valuable information for the operation and management of the treatment processes. Like any mathematical model, this model can be complemented or improved. Further development of models such as ASM2d, ASM3 or BSM2 would be beneficial. Also the mathematical model can be implemented in various software. In the future, implementing a mathematical model in the automatic process management would bring benefits to the operator.

Until that time, the model can achieve the following:

- Estimates the future evolution of the process as an input size changes;
- Can test which is the response of the process under operating conditions;
- Can be trained with process data;
- By simulating the mathematical model one can try an evolved leadership solution;
- Can provide useful information to those who lead such processes;
- Can be used to train and improve operators;

The present study provides the following information (and recommendations) to the operator:

1. Chapter 4.4 results: the mathematical model has applicability in the calibration of the measuring devices. Thus, by means of mathematical modeling, a conversion factor for the on-line probe (SO01) for the influence of the carbon concentration of the influent (UVAS Hach-Lange type) was determined. For the simulated period, a calibration factor of 12,828 was obtained for the first 17 days when the probe provided a qualitative signal at an average value of 64.40 nm.

2. Chapter 4.5 results: Modification of the temperature by one ° C in the water treatment bio-reactor results in a 3% change in the heterotrophic active ($X_{B,H}$) concentration in the system, a 1% change in the autotrophic active biomass concentration in the system ($X_{B,A}$). Although insignificant, lowering the temperature in the bio-reactor leads to a decrease in the denitrification processes and a significant increase in the ammonium nitrogen concentration in the effluent

(133%). It is reliable to build a neural network to predict the temperature of the influent based on atmospheric temperature (weather). On cooling, the network's query will estimate the temperature in the bioreactor and act in the process (increasing the suspension concentration in the bioreactor by lowering excess activated sludge flow from the system). Also, the warming of the weather will act in the process, increasing the excess activated sludge flow from the system. Practically, in this way, a process adjustment will be implemented before the perturbation occurs.

3. Chapter 4.6 results: The mathematical model (simulator) has shown that it is safe to introduce an external carbon source to optimize the denitrification process. The best results were obtained at the introduction of carbon intakes at times when the influent had the flow and maximum concentration of pollutants. The performances of the biological reactor are directly related to the availability of a carbon source. Chemicals such as methyl alcohol, ethyl alcohol, acetic acid or glucose can be sources of external carbon. All external sources of carbon can also be industrial waste. However, an examination, detailed analysis of each waste prior to recovery / disposal is necessary. No such treatment can be applied to any treatment plant. Transport or processing costs can make recovery / disposal of waste unfeasible. In such situations, internal carbon sources, rich in COD, must be examined by means of disintegration of sludge (pre-treatment) or pretreatment (fermentation of sewage, fermentation of primary sludge) [137].
The wastewater treatment plant, using the 3.3 tons / day carbon dioxide (COD) from the dairy industry, can optimize its water treatment process by introducing the carbon source flow between 11°°-15°°. The introduction of the carbon source can provide a 12.92% increase in the concentration of heterotrophic organisms in the aeration basin. Introducing the carbon source between 11-15 hours has the same effect as 3°C lowering the temperature in the bioreactor The external carbon source leads to a better removal of nitrogen from wastewater, improves the aeration process and reduces the energy costs of operating the entire sewage treatment plants. An estimated electricity saving of about 106 MWh / month is estimated, about 6,700 € / month (energy consumption gap between one winter month and one summer). By applying a processing fee (26 € / m^3) you can additionally get about € 23,000. The cost reduction can thus rise to 29,700 euros / month.

4. Chapter 4.7 results: The capacity of biomass to treat additional nitrogen is limited. An inhibition of denitrification processes is observed with increasing volumes of sludge liquor from centrifugation of the fermented sludge that are introduced into the treatment stream. In the case of implementation of a process management that foresees 8 hour / day dewatering centrifuges, a

small increase in total nitrogen (5.46%) in the effluent leads the process (at some times in time) very close of the maximum admissible (regulated) concentrations. In the event of an additional disturbance, the total nitrogen concentrations in the effluent may be exceeded. The implementation of such an exploitation scheme, with the use of dehydrating centrifuges 8 hours per day, requires complementary implementation of an advanced management strategy.

5. Chapter 2.2.2 investigation: It is recommended that the operator analyze the possibility of acquiring and equipping anaerobic fermenters with on-line sensors for: COD, TOC, VFA, alkalinity and biogas composition. The cost of investment for adequate on-line instrumentation and process automation for a biogas plant equipped with a generator capacity greater than 300 kW may account for 5-10% of the total cost of the plant. The implementation of an advanced control and management strategy for the fermentation plant can maximize the generation of generated electricity. The anaerobic fermentation plant can provide> 45% of the electricity required for the operation of the entire treatment plant (> 10.7 MWh / day). The minimum investment cost is estimated at ≈ 200.000 € and the cost of the supplies is estimated at ≈6.500 € / year (according to an estimate of Hach-Lange).

6. Chapter 5.3 investigation: Anaerobic co-fermentation means the simultaneous fermentation of two or more substrates. Anaerobic co-fermentation is a solution for lowering operating costs. Daily yields of between 2.5 ÷ 4 m^3 of biogas / m^3 bioreactor are reported in the centers in Europe that produce biogas by co-fermentation [99]. Zinc in the dairy industry (rich in lactose and carbohydrates), food waste or glycol may be co-fermented. In the literature, there are many data and industrial examples on the use of food waste. By applying a waste tax, wastewater treatment plants can obtain additional revenue. In the United States for food waste, sewage treatment plants apply a download fee of between 50 and 170 $ / tone [145]. The European Union produces about 88 million tons of food waste per year, about 173 kg per capita. If the EU produces about 865 kg per inhabitant per year, that means that 20% of the food produced is discarded [146]. Wastewater treatment plants can take advantage of food waste.

In literature, we find the example of Gloversville-Johnstown, NY, USA, which uses 45-60 m^3 of whey daily in the dairy industry [20], [13], [19] daily. With a processing capacity of only 41.640 m^3 of waste water per day compared to the 119.221 m^3 / day of the analyzed Romanian plant, respectively with a total capacity of the fermenters of only 10.600 m^3 compared to the 14.000 m^3 of the one in Romania, the station became energy-independent. The analyzed plant in Romania manages to cover about 45% of its energy needs by co-generating the produced biogas. If the station in Romania produces about 2.4 GWh of electricity annually, the one in the USA has been able to produce 6.6 GWh of electricity. The analyzed plant can daily harvest 40 to 60 m^3 of whey in the milk industry by co-fermentation. However, modifications of the hydraulic installation are required for their introduction into fermenters.

7. The mathematical model ASM1 + ADM1 developed for the researched industrial installation can be improved. Greenhouse gas emissions can be assessed. To reduce the impact of the plant on the environment, the process management can also be optimized to reduce pollutant emissions.

8. Separate sludge in the water treatment process may be subjected to mechanical pretreatments. By sonification the sludge entering the fermentation, the plant efficiency can be improved, the amount of biogas produced can be increased. Increasing the soluble organic substrate of excess active sludge shortens retention time in the fermenter from 13 to 6 days [14]

9. In a long-term development strategy for municipal wastewater treatment plants, they should be regarded as "integrated" centers for the disposal and recovery of organic waste generated by the community served.

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Annexes:

(1) WWTPs in Europe, USA and Canada that have implemented co-digestion:

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Energy self-sufficiency of full-scale WWTP with AD of sewage sludge and co-digestion of organic waste in North America (US and Canada) and Europe.

Plant	Location	Flow rate	Feedstock (Loading rate)	Digester capacity	Digester operation	Biogas cleanup/upgrading technology	Annual biogas production	Biogas utilization (CHP technology)	Energy self-sufficiency	Reference(s)
Average flow rate < 5 MGD										
Millbrae WPCP	CA, US	2 MGD	WAS (28,000)+FOG (3000)=31,000 GPD	2 × 1900 m³	Mesophilic HRT 38–58 d	N/A	N/A	1 MBTU (a) Boiler Microturbine	68%	[77]
Essex Junction WWTP	VT, US	2 MGD	Sludge+FOG+HSW (brewery and oily waste)	2 × 1350 m³	Two-Stage Mesophilic HRT 25–30 d	PSA-water stripper	1.7 GW h	2 × 20 kW Microturbine	38%	[15]
Grevesmuhlen WWTP	Germany	4 MGD	PS (10%)+WAS (60%)+Grease skimming sludge (30%)=1840 t TS/yr	2 × 1000 m³	Mesophilic HRT 17.5 d	N/A	1.95 GW h	210 kW IC Engine 1.7 GW h/year Electricity	100% Sale > 20%	[78]
Wolfgangsee-Ischl WWTP	Austria	5 MGD	Mixed PS+WAS	N/A	Two-Stage Mesophilic HRT 80 d	PSA	3.0 GW h	High-efficiency (34%) Cogenerator 1 GW h Electricity	100% Sale 10%	[60,61]
Velenje WWTP	Slovenia	5 MGD	Sludge+Organic waste (1.01 COD kg/m³/d)=1100 t/yr	2 × 1000 m³	Mesophilic HRT 20 d	N/A	2.8 MW h	365 MW h/year Electricity 1645 MW h/year Heat	N/A	[79]
Treviso WWTP	Italy	5 MGD	WAS+OFMSW (1 t OFMSW per 10 m³ WAS)	2000 m³	Mesophilic HRT 22 d	N/A	1.5 GW h	N/A	N/A	[80,81]
Average Flow Rate < 50 MGD										
Strass im Zillertal WWTP	Austria	6 MGD	Mixed BNR WAS+Trap grease+Crude glycerol+Food waste	N/A	Mesophilic	N/A	10 GW h	High-efficiency (38%) Cogenerator	100% Sale 20%	[59,82]
Watsonville WWTP	CA, US	7 MGD	WAS (83,333)+FOG (4500)=88,000 GPD	2 × 5700 m³	Mesophilic	N/A	N/A	600 kW Cogenerator	N/A	[77,83]
Boden WWTP	Sweden	10 MGD	Sludge (24,000)+Food waste (1200)=25,200 GPD	1300 m³	Thermophilic HRT 14–16 d	PSA	5.5 GW h	3.5 GW h/yr Plant heating 1.6 GW h/yr City heating network distribution 400 MW h Excess biogas upgraded to vehicle fuel	N/A	[84]
Viareggio WWTP	Italy	10 MGD	Sludge+OFMSW (1.21 kg VS /m³/d) = 350 t/d	1st: 3000 m³ 2nd: 1500 m³	Mesophilic HRT 20 d	N/A	2.2 GW h	N/A	N/A	[80]
Gloversville–Johnstown Joint WWTP	NY, US	11 MGD	Sludge+HSW (yogurt/cheese whey wastewater)	1st: 5700 m³ 2nd: 4900 m³	Two-Stage Mesophilic HRT 15 d	Activated carbon	28 GW h	6.6 < online > . < / online > GW h/year Electricity 9.0 GW h/year Heat	100%	[85]
Sheboygan Regional WWTP	WI, US	11 MGD	Sludge+FOG+HSW (dairy waste)	3 Primary 1 Secondary	Mesophilic	Condensation+Activated carbon	32 GW h	700 kW Microturbine 6 GW h/year Electricity 20 GBTU/year Heat	100%	[15,86,87]
Gresham WWTP	OR, US	13 MGD	Sludge (60,000)+FOG (9000)=69,000 GPD	2 × 3800 m³	Mesophilic HRT 18 d	N/A	17.2 GW h	2 × 400 kW Cogenerators 5 GW h/year Electricity 10.7 GW h/year Heat	100%	[74,88]
Douglas L. Smith Middle Basin WWTP	KS, US	15 MGD	Sludge (6700 t/yr)+FOG (3.23 MGY)	4 × 2000 m³	Mesophilic	N/A	35 GW h	2 × 1.06 MW IC Engine 5.4 GW h/year Electricity	50%	[43,89–91]
South Bayside System Authority Redwood City WWTP	CA, US	18 MGD	WAS (250,000)+FOG (3500)=253,500 GPD	3 × 5700 m³	Mesophilic	N/A	N/A	N/A	N/A	[77]
Baden–Baden WWTP	Germany	20 MGD	PS (15.9 MGD)+WAS (5.3 MGD)+Municipal biowaste (8.8 MGD) = 30 MGD	Hydrolyzer: 474 m³ Digester: 2 × 3000 m³	Hydrolysis: 42 °C, HRT 23 h Digestion 37 °C, HRT 14 h	N/A	28.3 GW h	N/A	N/A	[55]
Riverside Water Quality Control Plant (WQCP)	CA, US	30 MGD	PS (40,000)+WAS (30,000)+FOG (20,000)=90,000 lb VS/d	N/A	Mesophilic	Iron sponge+rotary lobe blowers+gas chilling+activated carbon vessels	N/A	2.5 MW Cogenerator 1.2 MW Fuel cell	N/A	[92]

F. Wayne Hill WRC WWTP, Gwinnett County	GA, US	33 MGD	Sludge (204,000)+FOG/HSW (23,250)=227,250 GPD	5 × 3800 m³ Egg-shaped	Mesophilic HRT 15 d	Iron sponge+activated carbon	46.2 GW h	2.15 MW Cogenerator 13 GW h/year Electricity	50%	[15,45,93]
South-Cross Bayou WRF, Pinellas County	FL, US	33 MGD	Sludge+FOG (2000–6000 dry lb/yr)	N/A	Mesophilic	N/A	N/A	1.4 MW Cogenerator	N/A	[15,94,95]
South Columbus WRF	GA, US	35 MGD	Sludge+FOG	1 CSTR	CSTR-Hydrolysis: 53 °C, HRT 6 d	PSA:	40 GW h	2 × 1.75 MW IC Engine	40%	[7,46,57,96,97]
				2 × 67 m³ PFR	PFR-Hydrolysis: 53 °C, HRT 30 min					
				2 × 4500 m³ Digesters	Digestion: 37 °C, HRT 15 d	Iron sponge+rotary lobe blowers+gas chilling+activated carbon vessels		11 GW h/year Electricity		
Prague Central WWTP	Czech Republic	42 MGD	Mixed PS+WAS (70 t VS/yr)	12 × 4800 m³	2-Stage Thermophilic HRT 25 d	N/A	115 GW h	3 × 1 MWe [(a)]+2 × 1.2 MWe Cogenerators 37.6 GW h/year Electricity	94%	[62,63,98]
Inland Empire Utilities Agency (IEUA) Regional Plant No. 1, Ontario	CA, US	44 MGD	Sludge+Dairy manure/Food waste (80/20)=1.53–3.10 kg VS/m³/d	N/A	3-Stage AG-MTM 1st Stage: 37 °C, HRT 3 d 2nd Stage: 55 °C, HRT 10 d 3rd Stage: 37 °C, HRT 15 d	PSA-water stripper	60 GW h	2.8 MW Fuel cell + 4.2 MBTU Heat recovery system	80%	[99,100]
Average Flow Rate < 100 MGD										
Des Moines MWRA WWTP	IA, US	59 MGD	Sludge+FOG+HSW = 0.5 MGD	6 × 10,000 m³	Mesophilic HRT 33 d	PSA	90 GW h	73 GW h/year Electricity 42 GW h/year Sale Cargill 9 GW h/year Heat	75%	[15,43]
Zürich Werdhölzli WWTP	Switzerland	67 MGD	Sludge (18,000)+FOG (5000)=23,000 t TS/yr	4 × 7250 m³	Mesophilic	N/A	41.4 GW h	High-efficiency Cogenerator	100%	[101,102]
East Bay Municipal Utility District WWTP, Oakland	CA, US	70 MGD	Sludge+FOG/Food waste/HSW	12 × 7500 m³	Mesophilic HRT 18 d	Activated carbon	90 GW h	3 × 2.1 MW IC Engines+4.6 MW Turbine =11 MW 55 GW h/year Electricity (10 GW h/year Sale)	100% Sale 20%	[103,104]
Gryaab WWTP	Sweden	92 MGD	Sludge (430,000)+FOG (5000)+HSW (4000)=439,000 t/yr	2 × 11,400 m³	Mesophilic	Amine absorption (COOAP™ Process)	60 GW h	Biogas sold to Goteborg Energi Co. for upgrading	N/A	[105]
Csepel WWTP	Hungary	93 MGD	Mixed PS+WAS from BNR Process (85 t TS/yr)	Thermophilic: 17,000 m³ Mesophilic: 6300 m³	1st Stage: 55 °C, HRT 12 d Exelys™ Hydrolysis: 165 °C, HRT 30 min 2nd Stage: 37 °C, HRT 15 d	N/A	95 GW h	39 GW h/year Electricity 20 GW h/year Heat	65%	[54]
Average Flow Rate < 500 MGD										
Village Creek WRF, Fort Worth	TX, US	110 MGD	Sludge+FOG+HSW (food processing waste, glycerin/organics acids from biodiesel facility)	14 × 4500 m³	Mesophilic	N/A	62 GW h	2 × 5.2 MW Turbines 2 Steam-Turbines	75%	[106–109]
Annacis Island WWTP, Vancouver	Canada	130 MGD	Sludge (0.69)+FOG (0.07)=0.76 MGD	4 × 12,000 m³	Thermophilic	N/A	132 GW h	IC Engines	50%	[83,110,111]

Plant	Location	Flow rate	Feedstock (Loading rate)	Digester capacity	Digester operation	Biogas cleanup/upgrading technology	Annual biogas production	Biogas utilization (CHP technology)	Energy self-sufficiency	Reference(s)
Point Loma WWTP	CA, US	175 MGD	Mixed PS+WAS (1 MGD)	8 × 13,600 m^3	Mesophilic HRT 30 d	PSA	193 GW h	2 × 2.25 MW IC Engines 34.3 GW h/year Electricity 53.5 GW h/year Heat Excess biogas upgraded and sold to power off-site 4.5 MW fuel cells	100%	[46,112,113]
Davyhulme WWTW, Manchester	England	200 MGD	Mixed PS+WAS (91,000 t TS/yr)	2 × 7500 m^3	Cambi™ Hydrolysis: 165 °C, HRT 20 min Digestion: 40 °C, HRT 18–19 d	N/A	238 GW h	12 MWe IC Engines 87.6 GW h/year Electricity	96%	[114–116]
Joint Water Pollution Control Plant, Carson	CA, US	300 MGD	Sludge (91%)+Food waste (9%)=4.84 MGD	24 × 14,200 m^3	Mesophilic HRT 20 d	Venturi scrubbers+coalescing filter+cooling coils	484 GW h	3 × 10 MW Turbines 175 GW h/year Electricity Upgraded biogas injection to CNG fueling facility (300,000 GGE)	97%	[117,118]
Blue Plains AWWTP, Washington DC	DC, US	375 MGD	Mixed PS+WAS	4 × 14,200 m^3	Cambi™ Hydrolysis: 165 °C, HRT 20 min	N/A	360 GW h	3 × 4.6 MW Turbines 103 GW h/year Electricity	33%	[52,76]