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MODELING AND SIMULATION OF ANAEROBIC MESOPHILIC DIGESTERS IN THE PRODUCTION OF BIOGAS AT CLUJ-NAPOCA WASTEWATER TREATMENT PLANT

Summary of PhD THESIS

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Part I - Overview and theoretical background

Chapter 1. General aspects

The global energy demand is growing rapidly and at the same time, concentrations of greenhouse gases (GHGs) in the atmosphere are rising rapidly with, fossil fuel-derived CO_2 emissions being the most important contributor. Another important global challenge is the security of energy supply, because most of the known conventional oil and gas reserves are concentrated in politically unstable regions.

In this context, biogas from wastes, residues, and energy crops will play a vital role in future. Biogas is a versatile renewable energy source, which can be used for replacement of fossil fuels in power and heat production, and it can be used also as gaseous vehicle fuel. Methane-rich biogas (biomethane) can replace also natural gas as a feedstock for producing chemicals and materials.

For biogas production, various process types are applied which can be classified in wet and dry fermentation systems. Most often applied are wet digester systems using vertical stirred tank digester with different stirrer types dependent on the origin of the feedstock. Biogas is mainly utilized in engine-based combined heat and power plants, whereas micro-gas turbines and fuel cells are expensive alternatives which need further development work for reducing the costs and increasing their reliability. Gas upgrading and utilization as renewable vehicle fuel or injection into the natural gas grid is of increasing interest because the gas can be used in a more efficient way. The digestate from anaerobic fermentation is a valuable fertilizer due to the increased availability of nitrogen and the better short-term fertilization effect. Anaerobic treatment minimizes the survival of pathogens which is important for using the digested residue as fertilizer (Weiland, 2009).

The production of biogas through anaerobic digestion offers significant advantages over other forms of bioenergy production. It has been evaluated as one of the most energy-efficient and environmentally beneficial technology for bioenergy production (Fehrenbach et al. 2008).

Biogas is a highly reliable source of energy. To date, biogas is the only technologically fully established renewable energy source that is capable of producing heat, steam, electricity and vehicle fuel. It is, in the true sense of the word, a versatile energy source, with low CO_2 emissions (A.Wellinger, 2011)

Anaerobic digestion has been worldwide used for the treatment of numerous types of organic wastes (Mata Alvares et al, 2000). Anaerobic digestion of the municipal sludge wastes under mesophilic or thermophilic conditions can contribute efficiently in organic waste reduction and biogas production (Bolzonella D., 2003).

Anaerobic processes have been widely used for the treatment of municipal and industrial wastewater, sludge and agricultural wastes. Compared to aerobic methods, they are frequently more cost-efficient, they have a lower surplus sludge production, and reactors can be run with higher volumetric loads and thus smaller volumes. (Wichern M., et al, 2009).

1.1. Thesis motivation

Anaerobic digestion (AD) is the most conventional way to produce methane-rich biogas, which has great potential to replace the fossil fuel used in multiple applications. Many countries and companies are involved in the design and construction of AD systems. Both efficient and economical AD performances are extremely important to promote worldwide adoption of this technology. Empirical methods have been traditionally used to scale up AD facilities, but these have required construction of expensive prototype systems and time-consuming studies. Alternatively, design and optimization of AD processes for biogas production can be enhanced via validated mathematical models developed from mechanistic studies that lead to a more in depth understanding of the very complex transport phenomena, microbial biochemical kinetics, and stochiometric relationships associated with AD.

Wastewater treatment has become an increasingly important industrial process. AD is a green technology involving the generation of methane-rich biogas via the biological degradation of regionally available biomass like wastewaters, agricultural and municipal solid wastes. AD processes have for many years been used to treat and sanitize sewage sludge waste from aerobic wastewater and animal manure, reduce its odor and volume, and produce useful biogas (Yu L. et al, 2013) in turn is a first generation, renewable biofuel that offers the prospect of replacing fossil fuels in the transportation sector and limiting the net greenhouse gas emissions implicated in climate change.

Anaerobic conversions are among the oldest biological process technologies utilized by mankind, initially mainly for food and beverage production. They have been applied and developed over many centuries, although the most dramatic advances have been achieved in the last few decades with the introduction of various forms of high-rate treatment processes, particularly for industrial wastewater. High organic loading rates and low sludge production are among the many advantages anaerobic processes exhibit over the other biological unit operations. But the one feature emerging as a major driver for the increased application of anaerobic processed is the energy production.

There are several benefits expected from implementing ADM1 (a generalized model of anaerobic digestion) at Cluj-Napoca WWTP:

- Increased model application for full-scale plant design, operation and optimisation;
- Further development work process optimisation and control, aimed at direct implementation in full-scale plant;
- Common basis for further model development and validation studies to make outcomes more comparable and compatible;
- Assisting technology transfer from research to industry.

An energy efficiency and techno-economical investigation of anaerobic digestion technology for the CHP cogeneration unit at Cluj-Napoca WWTP, is also necessary to detect maximum concentrations in biogas production, which helps minimizing the costs at Cluj-Napoca Municipal Wastewater Treatment Plant.

Co-digestion is an efficient suggested method to improve benefits and performance in a WWTP, so a case-study of co-digestion and state-of-the-art technology and equipment at Budapest South-Pest Wastewater Treatment Plant has been investigated during the international mobility in Budapest.

1.2. Thesis objectives

The present thesis has been proposed to investigate the complex process of anaerobic digestion in the production of biogas at conventional wastewater treatment facilities.

The first objective of the thesis is to model and simulate the anaerobic digestion process, using Matlab/Simulink, based on ADM1 Batstone model 2001 and to adjust it the design parameters and technological process lines of Cluj-Napoca WWTP. The specific design plant data have been modified and integrated to the original model and also aspects regarding mixing and internal operational sludge temperature of digesters. A sensitivity analysis has been performed in order to establish the most influential process parameters over the model.

The second objective is to provide a guideline with valuable information regarding the anaerobic digestion process parameters, inside the digesters for further optimization of the biogas production, minimizing the costs and maximizing the benefits and most importantly for process control. This solves the „black-box” problem of the plant regarding the anaerobic digesters with respect to the sludge composition and bio-chemical transformation phases inside the mesophilic methanetanks.

Due to the major importance of a sustainable profitability of the plant, a techno-economical investigation of the CHP system has been made, being identified as a third objective, which has developed more ideas for a more efficient biogas production.

Forth objective has been proposed for an individual study-case on co-digestion process at Budapest WWTP, which has been appropriate to be investigated, in order to research the benefits of the process added to the mesophilic treatment of activated sludge in a municipal WWTP. Performance of mesophilic activated sludge digesters vs. thermophilic digesters treatment in co-digestion together with the state-of-the-art technology and equipment are presented.

1.3. Thesis structure and content

The present thesis structure is as follows: Part I – *Overview and theoretical background*, Part II – *ADM1 Model*, Part III –*Simulations*, Part IV – *General conclusions*.

Part I of the thesis includes five chapters.

In Chapter 1 entitled “General aspects”, the thesis motivation, objectives, structure and a summary are presented. A short introduction gives a general description of the current status of biogas production and presents the advantages and challenges of the biogas technology through anaerobic digestion, on today’s biogas market.

Chapter 2 entitled “Cluj-Napoca WWTP Design” presents plant characteristics and design parameters, data which is further used in the ADM1 model integration and simulations.

Chapter 3 “Technological process” describes the treatment processes for the sludge line and biogas line. The technological up-grade of the biogas is presented through desulphurization procedure.

Chapter 4, which is entitled “Characterization of mesophilic anaerobic digestion”, offers a description of the mesophilic anaerobic digestion process.

In Chapter 5, process monitoring of main parameters measured at Cluj-Napoca WWTP for the sludge line, in biogas production are discussed. Various methods for determining the sludge composition, that have a great influence over AD and ADM1 respectively have been proposed.

In Chapter 6 the foam bulking problems are addressed, since they are very common at WWTPs and short-term and long-term control methods are presented.

In part II, starting with Chapter 7 “ADM1 Theoretical Model”, focuses on theoretical aspects of the model, conversion processes, biochemical and physio-chemical processes, dynamic state variables, kinetics and differential and algebraic equation assessing the anaerobic digestion process.

Part III consists of Chapter 8 “ADM1 model adapted to industrial scale at Cluj-Napoca WWTP”, Chapter 9 “Sensitivity analysis”, Chapter 10 “ADM1 Simulations” and Chapter 11 “Energy efficiency study” and presents the results obtained in the experimental part of this thesis, using MATLAB/Simulink®.

The final chapter, Chapter 12 called “Solutions for biogas augmentation” presents the work realized during author’s four months research internship at Budapest South-Pest WWTP, investigating co-digestion through thermophilic digesters and a two-stage biological filtering by Organica® Food Chain Reactor (FCR) to increase treatment efficiency. Co-digestion has been proposed for further implementation at Cluj-Napoca WWTP, due to the clear benefits.

The last part, Part IV “General conclusions” which emphasizes the overall conclusions drawn from the thesis the most important findings from this research and also presents future work perspectives and author‟s personal contribution and publications.

The entire Part III, and Chapter 6 represent the author’s personal contribution of the thesis.

1.4. Summary

Wastewater treatment has become an increasingly important industrial process. Anaerobic digestion (AD) is a green technology involving the generation of methane-rich biogas via the biological degradation of regionally available biomass like wastewaters and municipal solid wastes. AD processes have for many years been used to treat and sanitize sewage sludge waste from aerobic wastewater, reduce its odor and volume, and produce useful biogas.

The present thesis has as a main objective to adapt The Anaerobic Digestion Model No. 1 (ADM1), Batstone 2001, to Cluj-Napoca Wastewater Treatment Plant with industrial data. The specific design plant data has been introduced and integrated into the original mathematical model by using MATLAB/Simulink. A sensitivity analysis has been performed in order to establish the most influential process parameters over the model.

Modeling and simulation results serve as an important guideline in the optimization and process control for plant operators and other specialists in the anaerobic digestion field.

Foam bulking problems have been adressed, due to its frequent occurrence a WWTPs. Short and long-term methods for process control used at Sofia Kubratovo WWTP, are useful tools for other plant operators confronting with these malfunctions.

Due to the major importance of a sustainable profitability of the plant, a techno-economical investigation of the CHP (Combined Heat & Power) co-generation system has been made, minimizing the costs and maximizing the benefits at Cluj-Napoca Wastewater Treatment Plant. Biogas augumentation solutions have been proposed. For the biogas augumentation a case-study on co-digestion at South-Pest Budapest WWTP has been made.

Keywords: ADM1, modeling, simulation, anaerobic digestion, activated sludge, biogas

Part III – Simulations

Chapter 8. ADM1 model adapted to industrial scale at Cluj-Napoca WWTP

8.1. Redimensioning

For the redimensioning of the model the following assumptions have been made:

- All 4 digesters are represented by a single tank
- The sludge composition is completely mixed
- All physico-chemical properties of the sludge ramain the same in the whole volume of the methanetank
- Output heat exchanger sludge temperature is the same as the fermenter's sludge temperature
- There are no chemical or biological reactions inside the pipes, only inside the methanetanks

Two case scenarios have been made for each of the two components integration, integration of heat exchangers to the ADM1 original model and integration of recirculation of biogas for mixing purposes respectively, which are investigated in the next 2 subchapters.

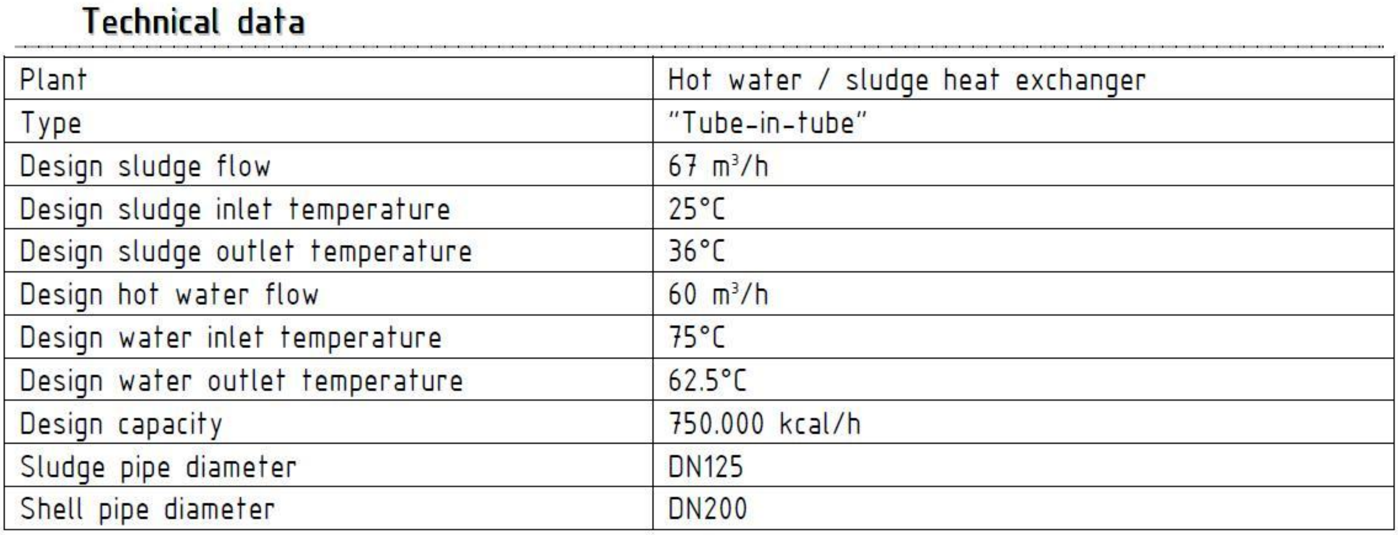
8.2. Integration of heat exchangers

The exchanger unit consists of a bundle of sludge tubes that are concentric with and located inside of larger diameter water tubes. Hot water is usually pumped from a boiler (or another type of hot water generator) to the exchanger. Sludge is pumped to the exchanger by dedicated pumping units. When heat transfer is desired, the hot water pump is energized to produce counter flow circulation of the water to the sludge flow.

Sludge flows through the smaller center tube, while water flows in the annular space formed by the outside of the smaller pipe and the inside of the larger pipe. With the counterflow piping arrangement, the mean temperature differential between the two fluids is maximized, which results in the most efficient transfer of heat from the water to the sludge.

The high turbulence of the flow in a tube-in-tube exchanger further improves the transfer characteristics by reducing the film coefficients between the fluids and the exchanger tubes. The tube-in-tube heat exchanger works as “static” equipment and therefore no attendance or setting made by the operator is required.

Table 29 Design parameters of the heat exchangers



Technical data

Plant	Hot water / sludge heat exchanger
Type	“Tube-in-tube”
Design sludge flow	67 m³/h
Design sludge inlet temperature	25°C
Design sludge outlet temperature	36°C
Design hot water flow	60 m³/h
Design water inlet temperature	75°C
Design water outlet temperature	62.5°C
Design capacity	750.000 kcal/h
Sludge pipe diameter	DN125
Shell pipe diameter	DN200

The central heating system has the role of preheating the sludge from the fermenters and produce sufficient thermal energy for the sludge heating but also for the WWTP buildings, with the following components:

- Heat exchanger water-sludge
- Digester sludge recirculation pumps
- Hot water recirculation pumps
- Biogas boilers
- Control pannels and sludge line control.

The sludge is heated through the hot water produced by the biogas boilers and/or methane produced by local public network.

It has the following measuring instruments and control strategies:

- Motorised valves on the primary and secondary sludge entry and flow control measuring units
- Input and output heat exchanger temperature measuring device
- Gas senzors alarm
- Fans for the air exchange in the heating system chamber

- Electrovalve for the gas lines shut down

The characteristics of the equipment are presented in Table 31.

Table 31 Heating system dimensioning

COMPONENT	CHARACTERISTICS	MEASURING UNIT	DIMENSIONS
Heat exchanger water/sludge	Unit	No.	2
	Type		Tube-in-tub
	Capacity	kcal/h	750.000
	Material	-	Stainless steel
	Unit	No.	4+4 reserve
Recirculation heated sludge pumps	Type	-	Mono-screw
	Flow		50
	Manometric Hight	bar	1
	Installed power	kW	7,5
Boiler	Unit	Nr.	4
	Type	-	Biogas/methane
	Capacity	kcal/h	750.000
Recirculation hot water pumps. Exchanger	Unit	Nr.	4+1 reserve
	Type	-	centrifuge
	Flow	m^3/h	60
	Manometric Hight	m	10
	Installed power	kW	3

When the heating system is turned on, it is supposed that there is not enough biogas necessary for the sludge heating. As a consequence, natural gas is being used from the national grid, until the system is self-sustainable on biogas produced from the plant. The sludge pumped into the heat exchangers and from the fermenters, are introduced with the help of the pumps (primary sludge pumps, secondary sludge pumps, recirculation sludge pumps), so that the thermal shocks are avoided.

Heat exchangers are used to heat the sludge to be recycled in anaerobic fermenters. The base module is a pair of concentric tubes: sludge flows through the inner pipe, while water (circulation counter) circulates through the empty space between the two pipes (Figure 43). If there are coupled in series more base modules, the heat exchangers obtain the desired total power. 180 ° bends and flanged connections ensure hydraulic connections of the two circuits. Each heat exchanger is provided with support frame and mineral wool pipe insulation in exterior.

Figure 43 Heat exchangers at Cluj-Napoca WWTP

In general, this system has been designed for the following divisions:

- Primary sludge – 13%
- Secondary sludge – 25%
- Recirculation sludge – 62%

Only in the heating/mixing faze of the fermenters or when there is no fresh sludge for input, are the recirculation pumps in operation.

The role of these pumps is to mix, from bottom to top, the whole sludge contained into the fermenters and to assure a constant temperature in the methanetanks (35°C-38°C) to replace the temperature loss which takes place from the digesters‟ walls.

The heating system is controlled by the amount of necessary heat detected from the temperature sensors, located at the entry and evacuation from the heat exchangers.

The operating parameters are the following:

- Input temperature of heat exchanger (varies from 10-37°C)
- Output temperature of heat exchanger (37°C during winter)

The boiler is operating almost constantly, due to the in and out temperature:

- Output temperature: 80°C
- Input temperature: 60°C

In order to protect the boiler from the thermal shocks on the input lines, if there is a high temperature input, the boiler modulates lower or turns off or the 3 way valve, directs the input flow to the output flow, without passing to the heating zone.

Also, the heating unit is supported also by the hot water that comes from co-generation, which has a priority role to the boiler. In other words, unless the co-generation heated water is not sufficient for the necessary thermal energy, the boilers are switched off when they do not cope for the replenishment. This is possible due to the 2 hot water collectors, where both input and output flows are being collected.

The following equations have been introduced in order to integrate the heat exchangers influence over the original ADM1 model:

$$\frac{dT_{ne}}{dt} = \frac{F_n}{v_i} \cdot (T_{ni} - T_{ne}) + \frac{K_T \cdot A_t}{v_i \cdot \rho_n \cdot c_{pn}} \cdot (T_{ae} - T_{ne}) \tag{131}$$

$$\frac{dT_{ae}}{dt} = \frac{F_a}{v_m} \cdot (T_{ai} - T_{ae}) + \frac{K_T \cdot A_t}{v_m \cdot \rho_a \cdot c_{pa}} \cdot (T_{ae} - T_{ne}) \tag{132}$$

where,

F_n = 67·24; sludge flow [m^3/day]

F_a = 60·24; water flow [m^3/day]

v_n = 0.049; volume of interior sludge pipe [m^3]

v_a = 0.076; volume of exterior water pipe [m^3]

T_{ni} = 25 + 273.15; [K]

T_{ai} = 75 + 273.15; [K]

K_t = 16; heat transfer coefficient for stainless steel [W/(m^2·K)]
A_t = 1.57; heat transfer area [m^2]
ρ_n = 1100; sludge density [kg/m^3]
ρ_a = 1000; water density [kg/m^3]
cp_n = 3000; sludge specific heat [J/(kg·K)]
cp_a = 4185; water specific heat [J/(kg·K)]

The MATLAB® code in C++ language for the heat exchangers integration can be found in Appendix B.

8.3. Recirculation of biogas

For the recirculation of the biogas for the Case Scenario No. 1, the following input parameters have been used for the model:

- Volume of methanetanks 4 digesters*3,500 m^3
- Sludge flow input (primary+secondary sludge) 4 digesters*500 m^3/day
- Operational temperature 35°C/308 K
- Recirculation of biogas : 25%

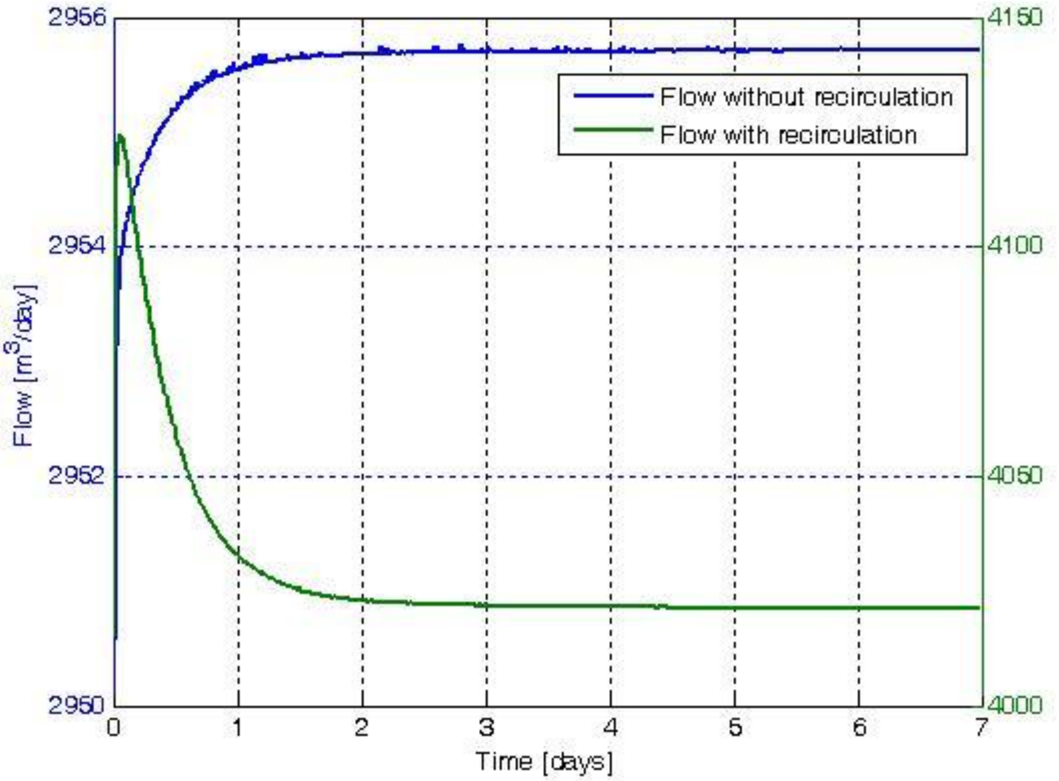


Figure 44 Integration of recirculation into the ADM1 modified model

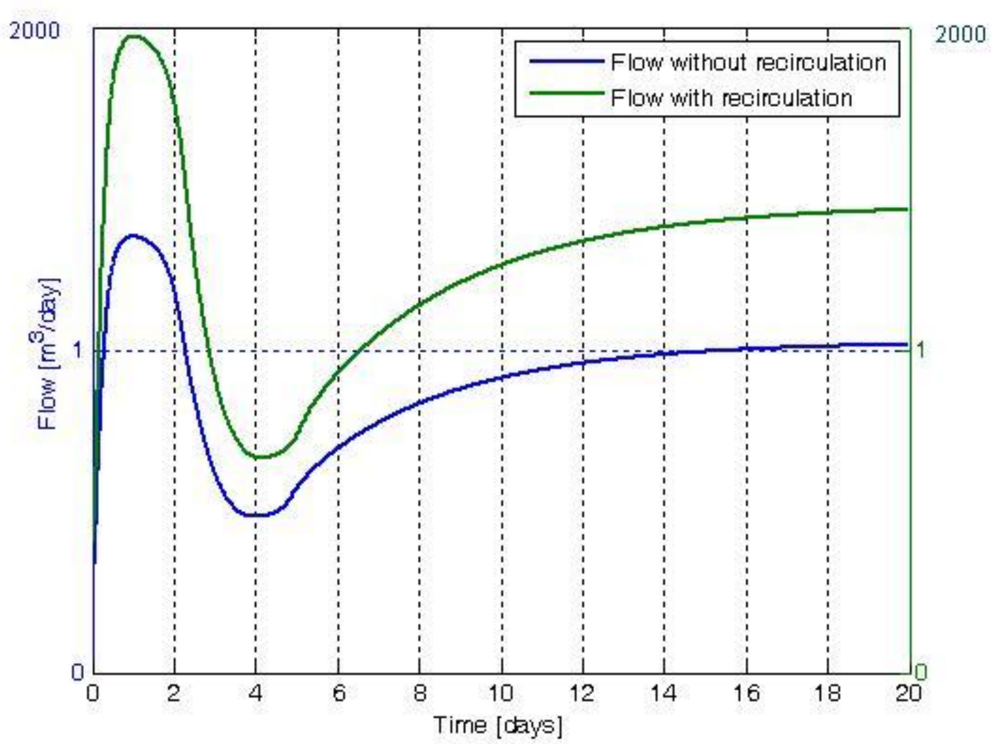


Figure 45 Recirculation biogas flows

In Figure 44 and Figure 45, it can be observed an increase of approximately 30% in biogas flow, with the integration of the biogas recirculation for mixing purposes. Biogas recirculation for mixing purposes is therefore an important parameter in the AD process for biogas output flow.

In Figure 46, the Simulink build model for recirculation is represented.

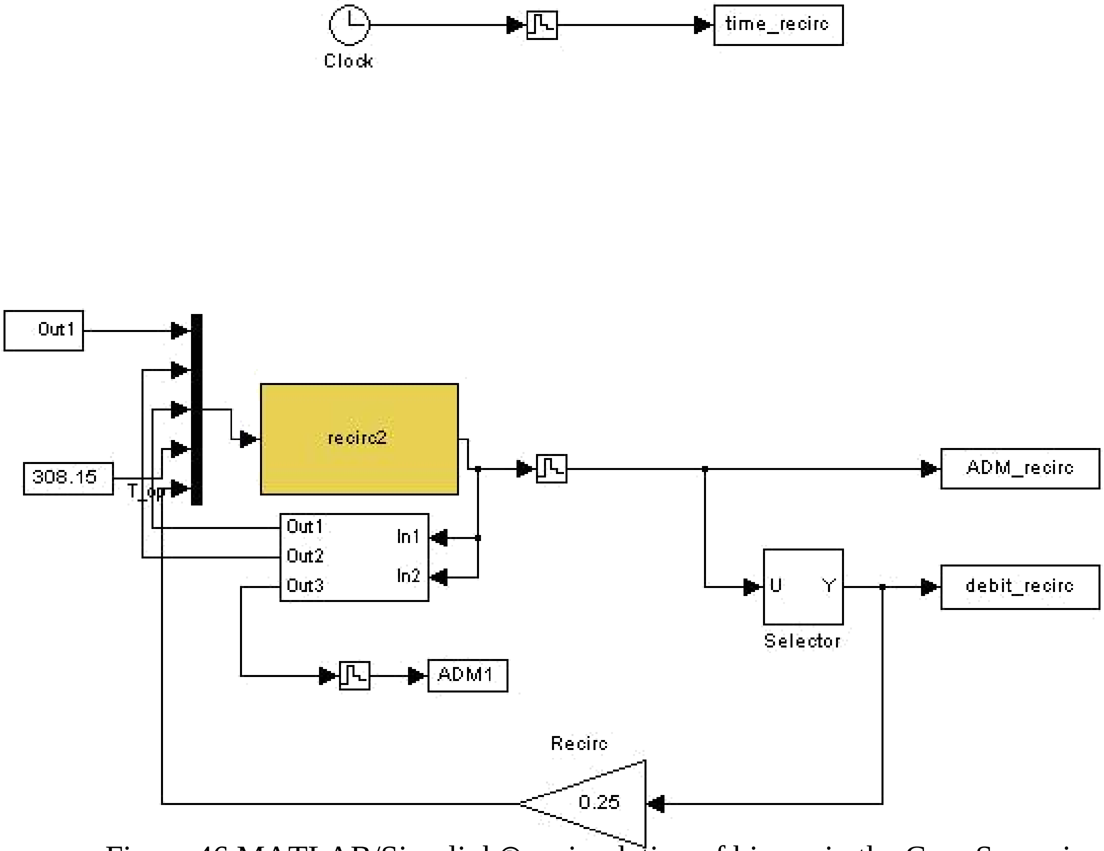


Figure 46 MATLAB/Simulink® recirculation of biogas in the Case Scenario no.1

Chapter 9. Sensitivity analysis

Zuza et al 2014, has discussed about the kinetic parameters in the ADM1 model that have been obtained by lab scale experiments; they have also been tested to give acceptable results for pilot scale operations. The model can also be applied to an industrial scale with minor modifications in either the kinetic or stoichiometric parameter. It is important to perform a sensitivity analysis of these parameters on the biogas production as well as methane concentration. The kinetic parameters showed minor variation in the biogas production rate and methane concentration, the stoichiometric parameters are considered to vary largely with the scale of production and the difference in feedstock composition. Hence these values have to be adjusted to fit in an industrial scale.

Each stoichiometric parameter is classified into three groups, to identify the sensitivity of these parameters to variation in processes and types of substrates. The group with the highest sensitivity is taken up first and the parameters are sorted in a descending order of their sensitivity.Each stoichiometric parameter is varied as within the acceptable range and the biogas flow rate and the methane concentration in the biogas has been recorded (Table 32).

Table 32 List of Stoichiometric Parameters

Parameter Description	Symbol	Hydrolysis	Acid
Soluble inert from Composites	$f_{sI,xc}$	0.1	0.7-1.2
Carbohydrates from Composites	$f_{ch.xc}$	0.2	0.16-0.23
Proteins from Composites	$f_{pr,xc}$	0.2	0.16-0.23
Lipids from Composites	$f_{li,xc}$	0.25	0.20-0.30
Nitrogen content of Composites	N_{xc}	0.002	0.0015-0.0023

Most of the industrial anaerobic digesters work on continuous mode. The continuous stir tank reactor (CSTR) model would be the best configuration to model them. A mathematical model has been developed in Simulink® to model the reactor in

CSTR configuration. The percentage change in the concentrations of methane and the total flow rate of biogas has been presented to analyze the sensitivity of each parameter.

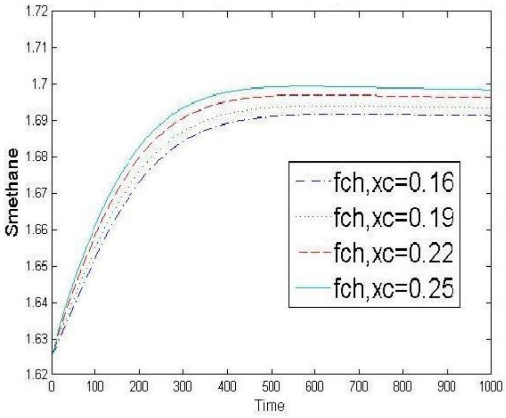


Figure 47 Carbohydrates from Composite

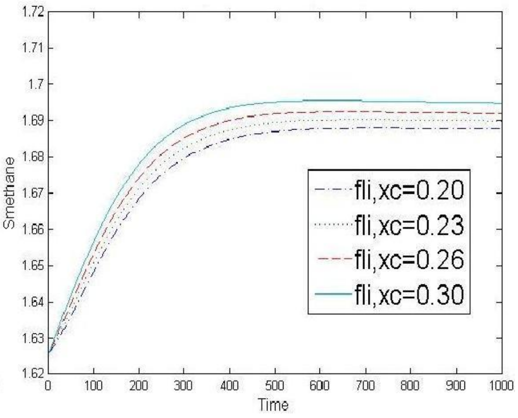


Figure 48 Lipids from Composite

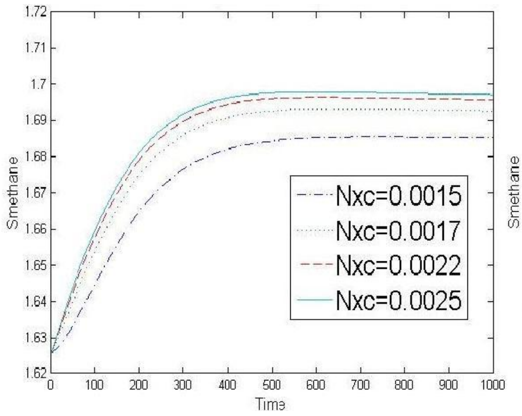


Figure 49 Nitrogen content from Composite

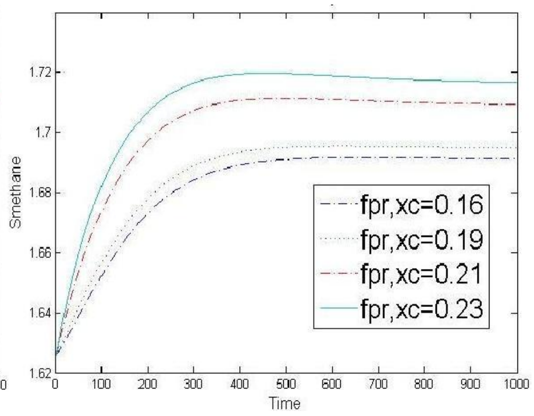


Figure 50 Proteins from Composite

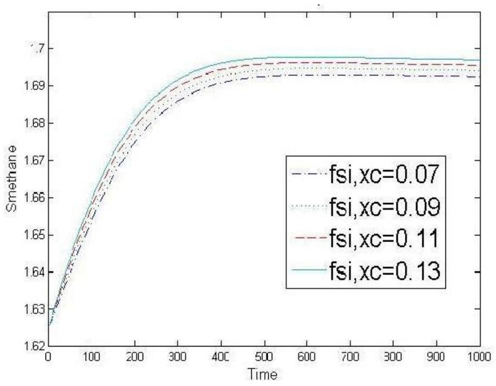


Figure 51 Inhibitors from Composite

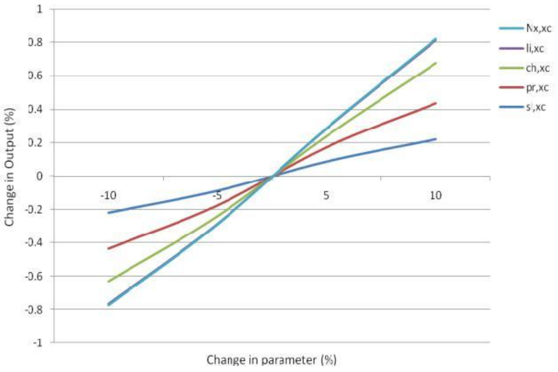


Figure 52 Parameter Sensitivity chart

Simulations have showed that there is not much of a difference in the biogas generation rate with the change in the selected stoichiometric parameters, but the concentration of methane gas showed significant variation with the change in the stoichiometric parameters. The Figure 47 to Figure 51 clearly shows this variation with time. To have a better understanding of this variation the final steady state value have been recorded and presented in Figure 52. The slope of each line provides the quantitative value of parameter sensitivity. The plot clearly indicates that each of these parameters has a different percentage variation with for the same percentage change in the input concentration. The exact percentage of change has been presented in the Figure 52.

From the results of the simulations, it is clear that the maximum deviation in the output is shown by the variation in the stoichiometric rations of nitrogen and protein, followed by carbohydrates and lipids and the least with the inhibitor concentration. This priority order can help in gaining an important insight on the extent and order of change made to fit the ADM1 model to the industrial data.

Optimizing the industrial process and providing an effective control strategy is the key factor of economical generation of biogas. The ADM1 with a minor change in parameters can accurately fit the industrial data. By generating the sensitivity plot for the variation in stoichiometric parameters, we have a clear understanding of its effects in methane concentration. The simulation results provide a sequential order for the parameters to be varied to fit the model to the industrial data. The sensitivity analysis shows the flowing priority order $\mathbf{f_{li,xc}}$, $\mathbf{N_{xc}}$, $\mathbf{f_{ch,xc}}$, $\mathbf{f_{pr,xc}}$, $\mathbf{f_{sI,xc}}$. After the successful generation of a mathematical model, it is possible to proceed to the next step in optimizing the process and also develop a control strategy for the digesters.

Further sensitivity analysis has been extended to understand the effects of various stoichiometric and kinetic parameters, input composition, carbon and nitrogen composition in the Anaerobic Digestion Model No. 1 (ADM1), (Nair A. and Zuza A., 2015).

The ADM1 mathematical model has been modified based on the design parameters from Cluj-Napoca WWTP. It has to be further calibrated to simulate the steady-state anaerobic digestion of activated sludge at municipal wastewater. For this purpose, it is extremely important to understand the effect of various unknown model parameters on the output variables. The modified model is able to predict the output with 2% error in biogas flow rate and 10% error in the digester pressure. The sensitivity analysis performed identifies the parameters that have a major impact over the output. This analysis also presents a list of parameters that have to be modified to calibrate the ADM1 model.

The ADM 1 (Batstone et al., 2002) has been used for the mathematical simulation of the fermentation of different substrates (Batstone et al., 2006). Since its development in 2002 and up to now the ADM1 has been tested and used on different substrates where a great number of research works are reported in the literature. Amongst others, investigations were done on mathematical simulation of special substrates of international interest, like starch (Sanders et al., 2000), blackwater (Feng et al., 2006) or olive pulp (Kalfas et al., 2006). Boubaker and Cheikh Ridha (2008) investigated on the mesophilic anaerobic co-digestion of olive mill wastewater with olive mill solid waste. Page, DI. et al. 2008, has modified the kinetic parameters of ADM1 in order to simulate dairy manure anaerobic digesters and thermophilic anaerobic co-digestion of olive mill wastewater and olive mill solid waste. Zaher, U. et al. 2009, has developed a general integrated solid waste co-digestion model, for optimization and assessment of co-digestion of any combination of solid waste streams. This very important tool estimates particulate waste fractions of carbohydrates, proteins, lipids and inerts and thus generates inputs for ADM1, which subsequently predicts biogas generation. In fact, anaerobic digestion of the organic fraction of the municipal solid wastes alone or combined with organic sludge can contribute efficiently to solid waste reduction and biogas production as described by many researchers: Zuza et al. 2015, Bolzonella et al. 2005, Mace et al. 2003 and Bolzonella et al. 2003, for solid waste treatment under mesophilic or thermophilic conditions.

Since the introduction of activated sludge models (ASMs) by Henze et al., 1987, the activated sludge processes have been studied using dynamic simulations in order to design, upgrade and optimize a range of configurations of the activated sludge unit in wastewater treatment plants (WWTPs). Later, the introduction of the anaerobic digestion model (Batstone et al., 2002) extended the modeling further to the sludge line.

Primary sludge from the primary settling tank and secondary sludge from the secondary clarifier are treated dried and mixed with polyelectrolyte and ferric chloride (Q), which are pumped subsequently into the digesters for the anaerobic digestion and biogas production. To maintain an inner constant process temperature of the digester, the sludge is recycled through heat exchangers. After the production of sufficient biogas, 20-25% of biogas is being recirculated into the digester for mixing purposes (Figure 53).

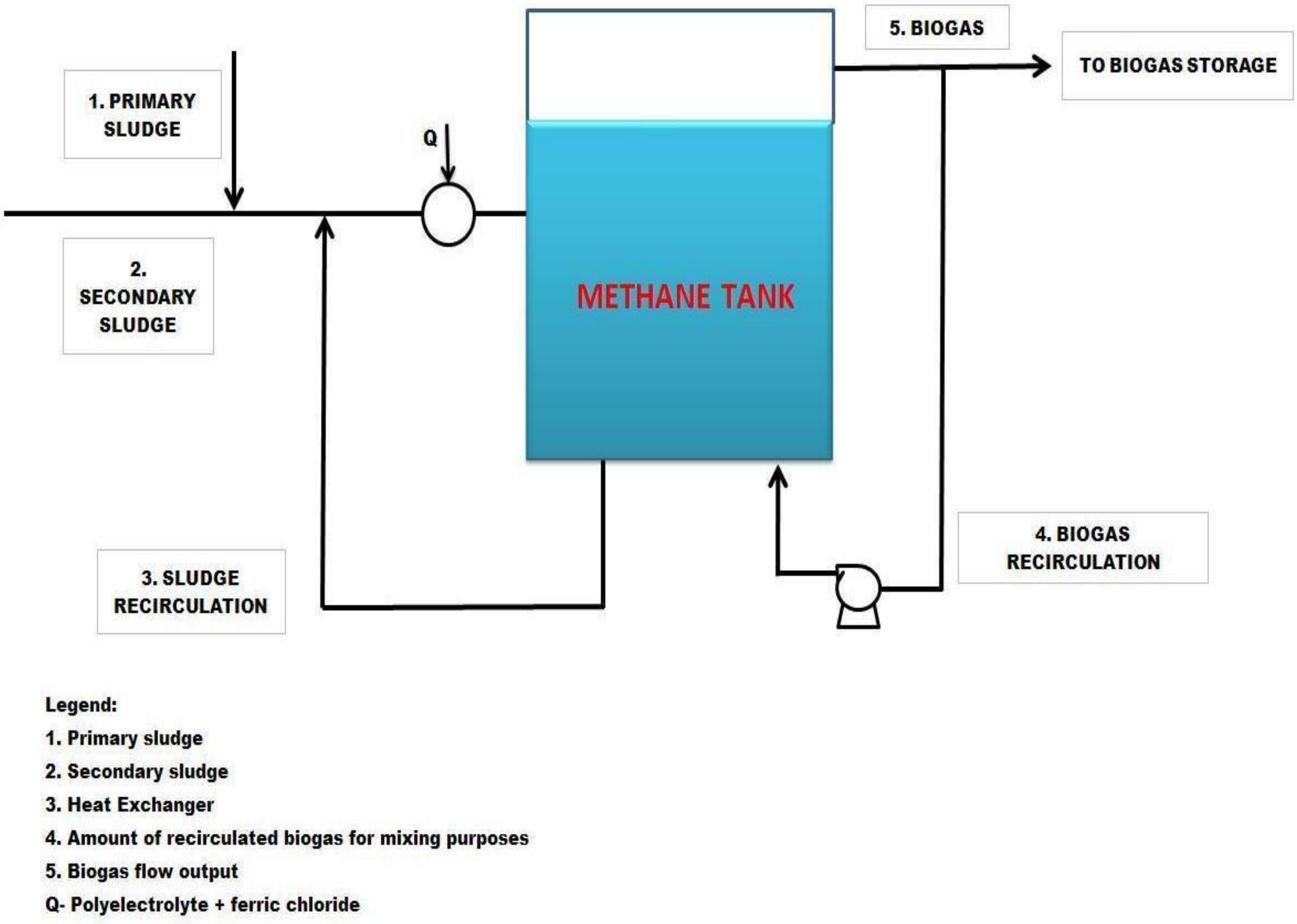


Figure 53 Sludge and biogas process lines

The ADM No.1 Simulink model (Rosen C. et al., 2006), has been modified based on the process conditions presented in Table 33. The balance equations presented (Batstone et al. 2002) has been modified slightly to include the sludge recycle and the gas recycles into the digester. Eq. 133 and Eq. 134 presents the change in the process conditions that are incorporated in the ADM1 model. Since the tank has been modeled as a perfectly mixed vessel, the influence of these recycles on physical conditions of mixing and other hydrodynamic effects can be ignored. A Simulink model has been build up to study the digester section of WWTP. The 4 digester model has been converted to a single digester system, to produce an equivalent model; this can be done by simple addition of all the process conditions because in real situation all the 4 digesters work parallel, under uniform flow conditions.

For Liquid stream:

$$\frac{dS_i}{dt} = \frac{q_{in} S_{in,i}}{V_{liq}} + \frac{q_{rec,s} S_i}{V_{liq}} - \frac{q_{out} S_i}{V_{liq}} - \sum_{j=1-19} \rho_j \, v_{i,j} \qquad (133)$$

S_i (i=1:24) – State variables
ρj – Kinetic rates
vi,j – Stoichiometric coefficients
$q_{rec,s}$ – Sludge recycle flow

For Gas section:

$$\frac{dS_i}{dt} = \frac{q_{rec,g} S_i}{V_{gas}} - \frac{q_{out} S_i}{V_{gas}} + k_L a_{gas} (S_{gas,liq} - K_{H,gas} P_{gas}) \qquad (134)$$

Gas –S_{CO2}, S_{CH4}, S_{H2}
k_L –Gas Liquid mass transfer coefficient $K_{H,gas}$–
Henrys Constant for the corresponding gas
$q_{rec,s}$ –Gas recirculation flow rate
P_{gas} –Partial pressure of the gas

The ADM No.1 model is often connected to an ASM-ADM converter (Nopens et al. 2009) which provides a detailed algorithm to convert the ASM1 model parameters to ADM1. Attaching a converter to the ADM No. 1 has two major advantages. Firstly this provides the need for having less complex ASM 1 input variables compared to the ADM 1 input which has about 25 input state variables. Secondly, it also would be convenient to link it to the Waste Water treatment model to create a Benchmark for a complete Waste Water Treatment Plant (BSM No.2).

Even after the implementation of ASM-ADM interface in the digester model, the input variables used are completely different from the values that are regularly monitored in the industry. There are no available methods for direct measurement of these input variables. The values of these inflow composition provided in the literature (Gernaey et al.2006) cannot be directly used in a digester model, due to the huge variations in waste-water sludge composition. Apart from the immeasurable input parameters, there is also a possibility of various parameters that could be different from those used in the ADM No. 1 by Batstone et al. 2002.

The default values of influent sludge composition, conversion parameters of the ASM-ADM converter, stoichiometric and kinetic parameters presented in the ADM1 fails to give the required tank pressure and methane production rates. Hence there is a need for calibrating these values to match the values obtained from the WWTP.

Before the model parameters are tuned to obtain the desired output, it is necessary to understand the effect of various parameters on these output variables.

Table 33 Inflow Composition

DISCRIPTION	PARAMETER ABBREVIATION
Soluble inert organic matter	S_I
Readily biodegradable substrate	S_S
Particulate inert organic matter	X_I
Slowly biodegradable substrate	X_S
Active heterotrophic biomass	$X_{B,H}$
Active autotrophic biomass	$X_{B,A}$
Particulate products arising from biomass decay	X_P
Soluble biodegradable organic nitrogen	S_{ND}
Particulate biodegradable organic nitrogen	X_{ND}

These parameters used to describe the model, have been obtained by experimentations and have been successfully implemented in various WWTPs, but as mentioned before, some of them still have a possibility of change. With such a huge list of variables that could be varied to fit in the data, a suitable choice has to be made to select the ones that can provide significant influence in the output variable. We also have to be careful to choose the parameters that are most likely to be affected by the change in feed composition. Table 33 shows the list of variables that are most likely to represent the parameters that is depended on the type of sludge. The parameters such as

Henry's law coefficients, acid-base equilibrium constant, acid-base rate constant are considered dependent completely on temperature and hence remain constant. The same is the case with the specific Monod maximum uptake rate, first order decay rate for biomass death, Monod half saturation constant, which are maintained same as the default values due to its extremely complex dependency function on the output variables.

Each of these parameters presented in the Table 34 are varied up to 10 times its actual value and its effect on the biogas production rate and the digester pressures are observed.

Table 34 Stoichiometric and kinetic parameters

Parameter	Description	UNIT
C_i	carbon content of component	kmoleC/kgCOD
k_La	gas–liquid transfer coefficient	d^{-1}
N_i	nitrogen content of component i	kmoleN/kg COD
$Y_{substrate}$	yield of biomass on substrate	kgCOD_X/kgCOD_S
$f_{product,substrate}$	yield of product on substrate	$kgCOD/kgCOD^{-1}$

Where,
i - Components/state variables used in the ADM1 (Batstone *et al.* 2002)

The comparison of the simulated variables and the industrial data is provided in Table 35. The Table clearly shows that the methane concentration clearly matches the values of the design parameters, but the flowrate and the digester pressure varies slightly from the design values. Hence a little tuning of parameters has to be done to match the values.

Table 35 Output parameters

OUTPUT	units	SIMULATED VALUE	INDUSTRY VALUE
Steady state pressure	Mbarg	49.42	25
Methane concentration	dimensionless	69.37	70%
Biogas flowrate	m^3/day	3312	3000

The result of the sensitivity exercise that has been performed has been presented in Table 35 and that have a positive influence on the pressure and biogas flowrate.

The ones presented in Table 36 have a negative influence on the total output parameters. These parameters are presented in the descending order of their sensitivities to have an idea about the order in which they have to be varied to get fit the ADM1 model to an industrial digester.

Table 36 Parameters that have negative effects on pressure and biogas production

Default value	Parameter	Description	mbarg	m^3/day	%P	%q
0.41	f_ac_su	Yield (acetates from sugars)	24.17	1631.8	-2.36	-50.87
0.08	Y_aa	Yield of biomass on amino acids	24.44	1649.4	-2.33	-50.34
0.007	N_aa	Nitrogen contend of amino acids	24.67	1665.5	-2.31	-49.86
0.13	f_bu_su	Yield (butyrate from sugars)	33.18	2239.4	-1.51	-32.58
0.27	f_pro_su	Yield (propionate from sugars)	34.50	2328.8	-1.38	-29.88
0.05	f_pro_aa	Yield (Propionate from amino acids)	36.71	2477.6	-1.18	-25.40
0.0217	C_fa	Carbon contend in fatty acids	42.26	2852.7	-0.65	-14.11
0.03	C_sI	Carbon content in Soluble inert	42.29	2854.9	-0.65	-14.04
0.1	Y_su	Yield of biomass on sugar	43.10	2909.3	-0.57	-12.41
0.02786	C_xc	Carbon content in Composite	44.24	2986.5	-0.47	-10.08
0.06	Y_fa	Yield of biomass in fatty acids	44.25	2986.9	-0.47	-10.07
0.04	Y_pro	Yield of biomass on propionates	44.83	3026.3	-0.41	-8.88

Table 37 presents the effect of changes that has been presented in the input composition. It has been observed the inserts have no effect on the output variables, but the rest of the compositions show its effect.

Table 37 Effect of changes in input composition

Default value	Parameter	Description	mbarg	m^3/day	%P	%q
0.03	C_pr	Carbon content in proteins	865.4	58412.2	76.8	1658.7
0.022	C_li	Carbon content in lipids	222.9	15045.1	16.3	353.0
0.0313	C_ch	Carbon content in carbohydrates	196.4	13258.6	13.9	299.2
0.95	f_fa_li	Yield (fatty acids from lipids)	120.1	8109.1	6.7	144.2
0.0313	C_ac	Carbon content in acetic acid	77.7	5248.1	2.7	58.0
0.4	f_ac_aa	Yield (acetic acid from amino acid)	71.3	4813.9	2.1	44.9
0.26	f_bu_aa	Yield (butyric acid from amino acids)	61.6	4158.4	1.2	25.2

The effect of 6 most important variables has been presented in Table 38.

Table 38 Effect of 6 most important variables

Default value	Parameter	Description	mbarg	m^3/day	%P	%q
14024	X_S	**Slowly biodegradable substrate**	**140.1**	**7102.2**	**184.7**	**113.8**
30315.3	X_{BH}	**Active Heterotrophic Biomass**	**210**	**8904.7**	**326.7**	**168.1**
744.6	X_{ND}	**Particulate biodegradable organic nitrogen**	**63**	**3489.4**	**28.0**	**5.0**
1643.7	X_{BA}	**Active Autotrophic bioass**	**52**	**3364.8**	**5.6**	**1.3**
33.3	S_S	**Readily biodegradable substrate**	**50.1**	**3321.9**	**1.8**	**0.2**
3.6	S_{ND}	**Soluble biodegradable organic nitrogen**	**49.99**	**3315.5**	**1.5**	**0.1**

The simulation outputs: biogas production rate, digester pressure and the methane concentration are presented in Figure 54-56.

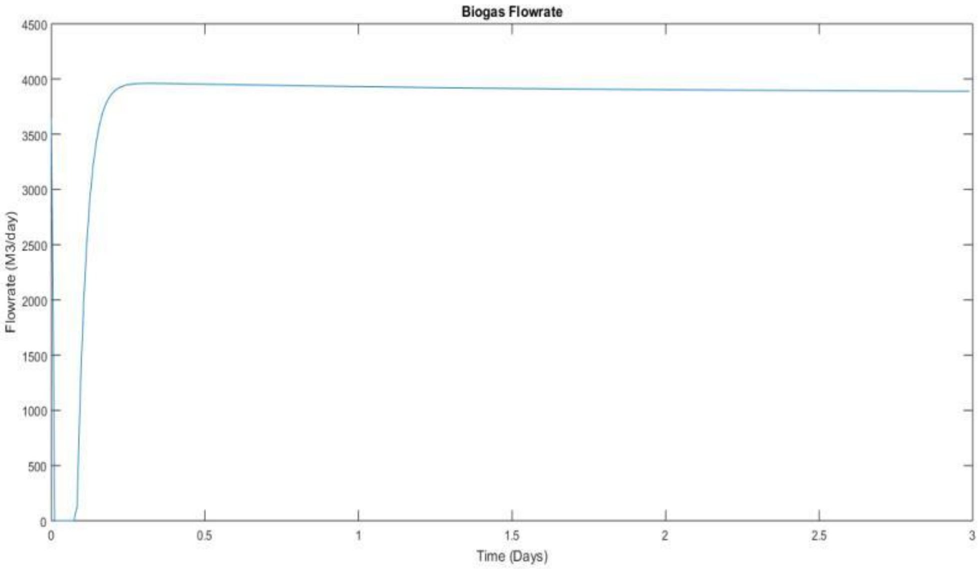


Figure 54 Biogas Flowrate in time

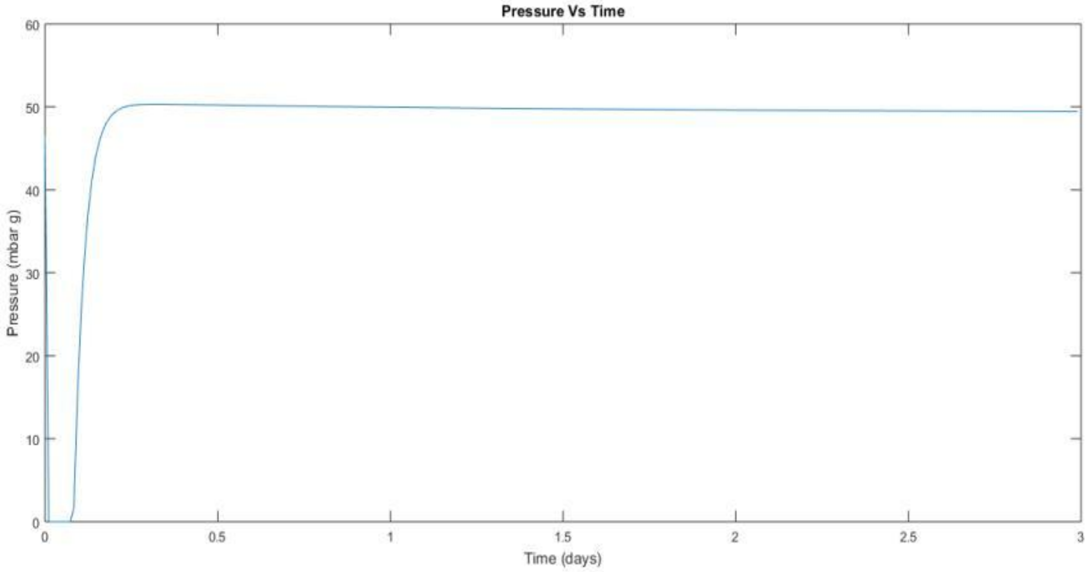


Figure 55 Pressure in time

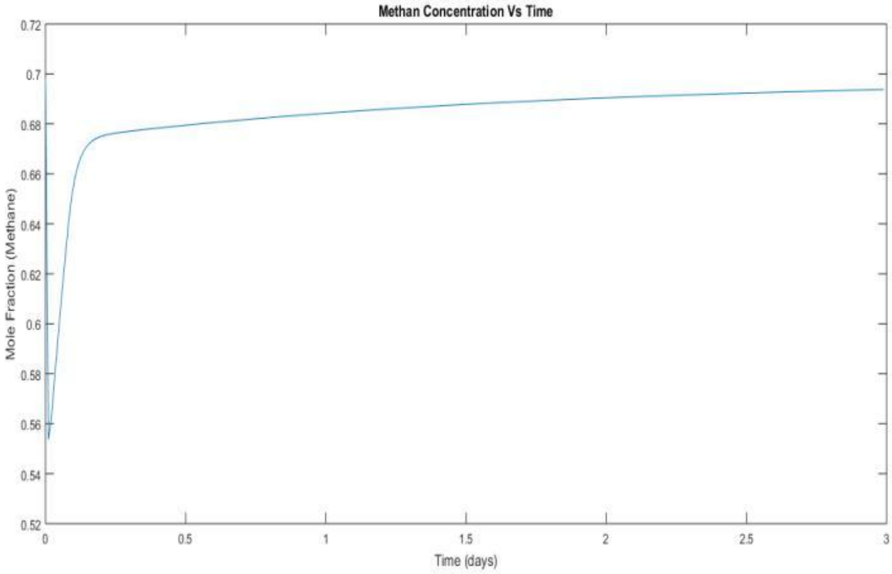


Figure 56 Methane concentrations in time

The parameter k_p which is the correlation factor between the digesters pressure and the gas flowrate has a unique influence in the model. In usual case it has been observed the increase in digester pressure usually results in an increase in the flowrate, but in this parameter, a rise in the digester pressure simultaneously decreases the flow rate. These results are presented in Figure 57. Due to this unique property, this parameter could be of vital use in tuning the ADM1 model.

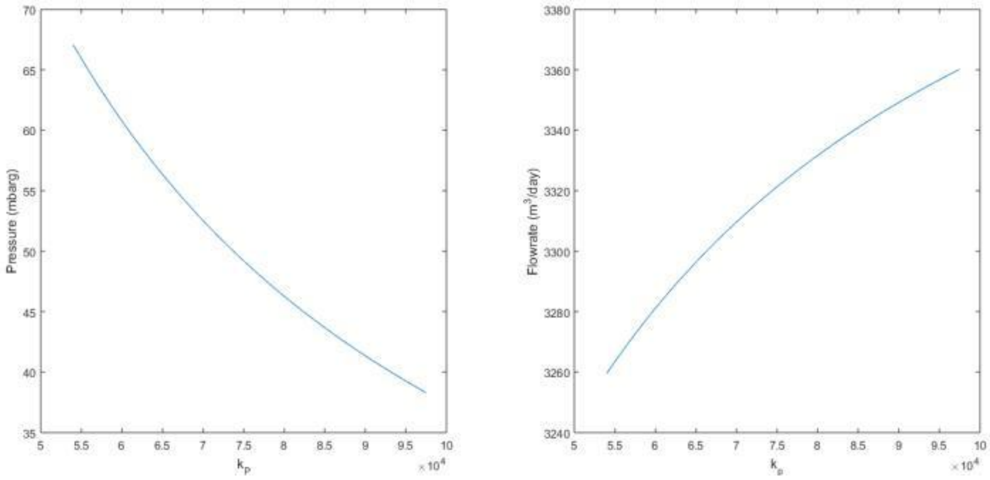


Figure 57 k_P function of pressure and flowrate

ADM1 mathematical model has been modified based on the design parameters from Cluj-Napoca WWTP and has to be further calibrated to simulate the steady-state anaerobic digestion of activated sludge at municipal wastewater, in the production of biogas.

The sensitivity analysis performed identifies the parameters that have a major impact over the output.

The simulation outputs: biogas production rate, digester pressure and the methane concentration fit the industrial data. The methane concentration (69.37) clearly matches the values of the design parameters (70%), but the flowrate (3,312 m^3/day) and the digester pressure (49.42 Mbarg-milibars guage pressure) varies slightly from the design values (3,000 m^3/day and 25 Mbarg respectively).

Parameter k_p which is the correlation factor between the digesters pressure and the gas flowrate has a unique influence in the model, because a rise in the digester pressure simultaneously decreases the flow rate.

Further calibration needs to be done to fit the ADM1 model to Cluj-Napoca anaerobic mesophilic digester, for biogas production.

For the Case no. 2 of ADM1 simulations the following parameters have been used for the ASM2ADM Interface (Table 39):

Table 39 ASM2ADM Interface values

ASM2ADM Paramater	Value
S_I	30
S_S	33.3
X_I	16235.7
X_S	14024.1
$X_{B,H}$	30315.3
$X_{B,A}$	1643.7
X_P	5038.9
S_{ND}	3.6
X_{ND}	744.6

The sludge input flow used was 540 m^3/day (primary sludge 260 m^3/day + secondary sludge 280 m^3/day), an input temperature of 35°C (308.15 K) with an internal temperature of 38°C (311.15 K), input pH of 7,volume of digesters 3,500*4 m^3 and recirculation of 10% of the gas and 30% liquid recirculation inside the digesters. In Figure 58, the Simulink build model is represented.

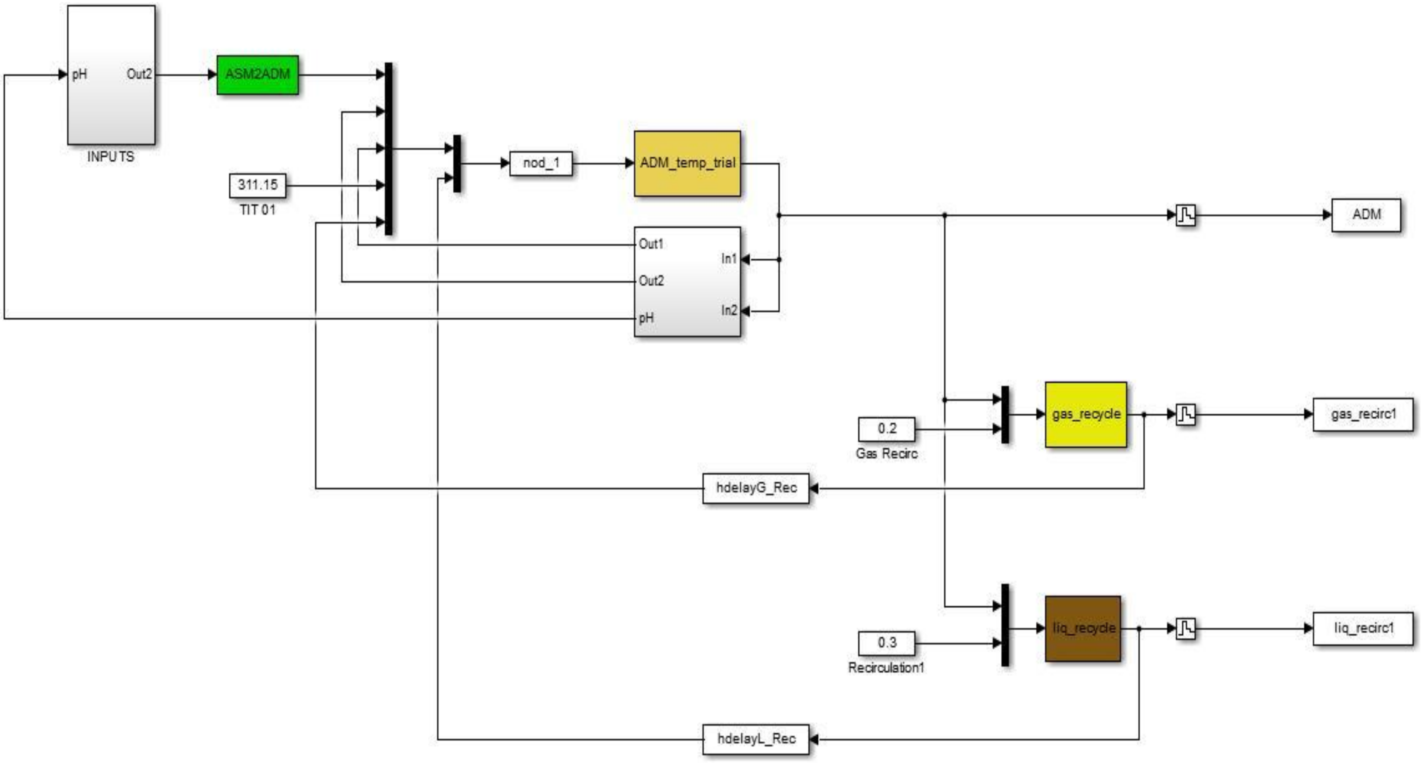


Figure 58 MATLAB/Simulink® gas and liquid recirculation Case Scenario no. 2

The most common way to calculate the gas flow is to set it equal to total gas transfer, corrected for water vapour Eq.135:

$$q_{gas} = \frac{R \cdot T}{P_{gas} - p_{gas,H2O}} \cdot V_{liq} \left(\frac{\rho_{T,H2}}{16} + \frac{\rho_{T,CH4}}{64} + \rho_{T,CO2} \right) \quad (135)$$

where,

P_{gas} – set headspace total pressure (normally 1.013) $\rho_{T,H2}$ – transfer rate of H_2

$\rho_{T,CH4}$ – transfer rate of CH_4

$\rho_{T,CO2}$ – transfer rate of CO_2

$p_{gas,H2O}$ – partial pressure of water vapours

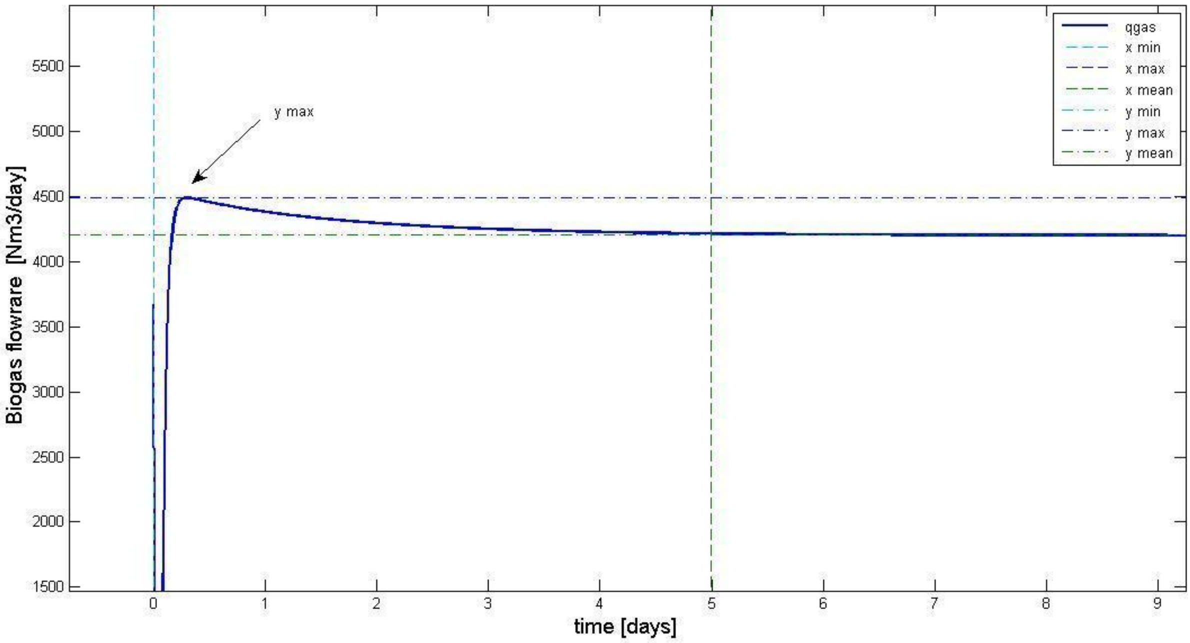
If the headspace is variable, or there is downstream processing of the gas, the gas flow can be calculated by a control loop in pressure. The gas phase pressure must be calculated from partial pressures Eq 136., and the flow calculated for a restricted flow through an orifice Eq.137.

$$P_{gas} = p_{gas,H2} + p_{gas,CH4} + p_{gas,CO2} + p_{gas,H2O} \tag{136}$$

$$q_{gas} = k_p\left(P_{gas} - P_{atm}\right) \tag{137}$$

where,

k_p – pipe resistance coefficient (m^3/d·bar)



P_{atm} – atmospheric pressure

Figure 59 Simulated biogas flowrate (q_{gas})

In Figure 59 the simulated biogas flowrate can be observed. The maximum biogas flowrate reaches a value of 4,500 Nm^3/day in the first day and after approximately 4-5 days it stabilizes to a constant value of 4,202 Nm^3/day.

In Figure 60 it can be observed the simulated biogas pressure [bar], which reaches a maximum of 1.07 bar in the first day. After 4-5 days the biogas pressure is almost constant at 1.06 bar.

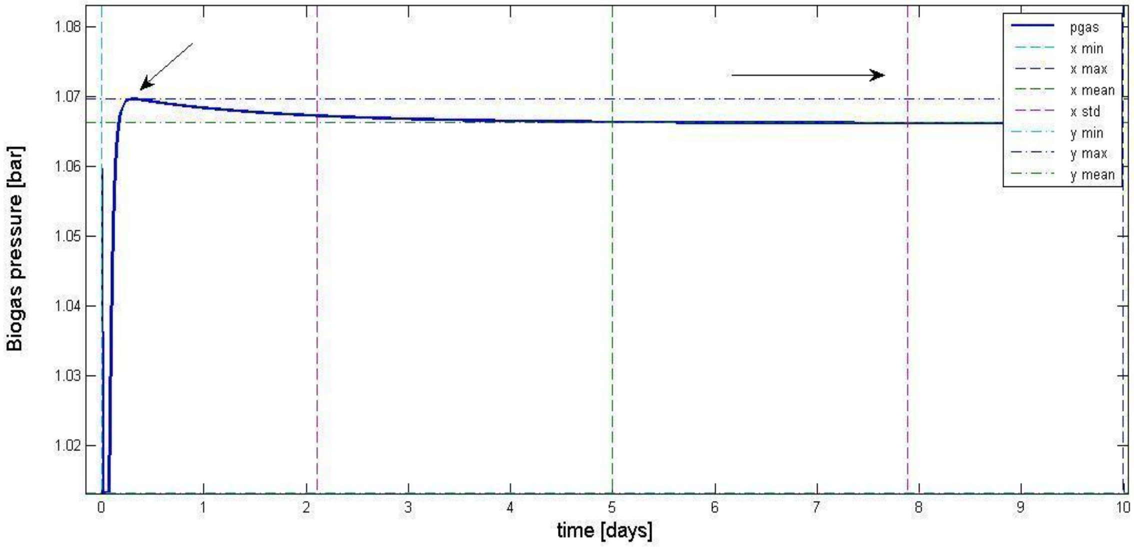


Figure 60 Simulated biogas pressure (pgas)

In Figure 61 the CO_2 partial pressure is simulated. The CO_2 partial pressure reaches 0.525 bar and then decreases to 0.48 bar and after 5-6 is starting to stabilize to a constant value of 0.47 bar.

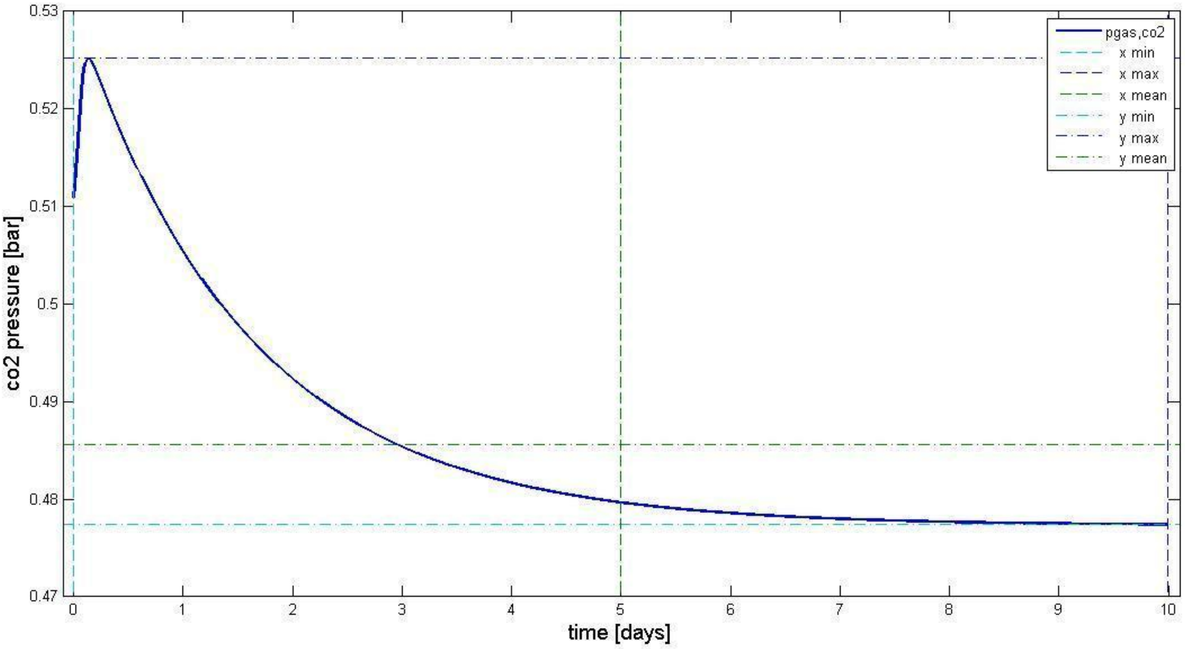


Figure 61 Simulated CO_2 partial pressure (pgas,co2)

In Figure 62 is simulated the partial pressure of methane. It increases in the first day and following days until it reaches a constant value of 1.2 bar, after approximately 5 days.

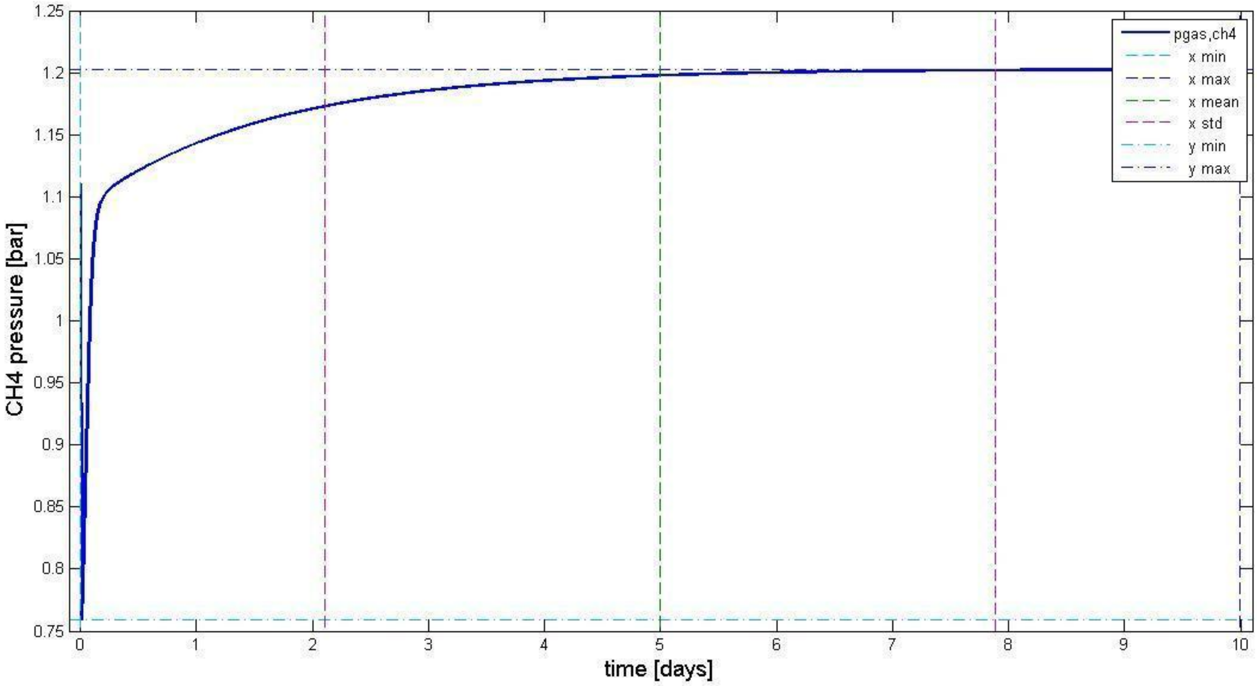


Figure 62 Simulated methane partial pressure (pgas,CH4)

In Figure 63 the simulated H_2 partial pressure is represented. The values are quite low; from 0.0259 bar drops to $2.8 \cdot 10^{-4}$, remaining constant after first hours.

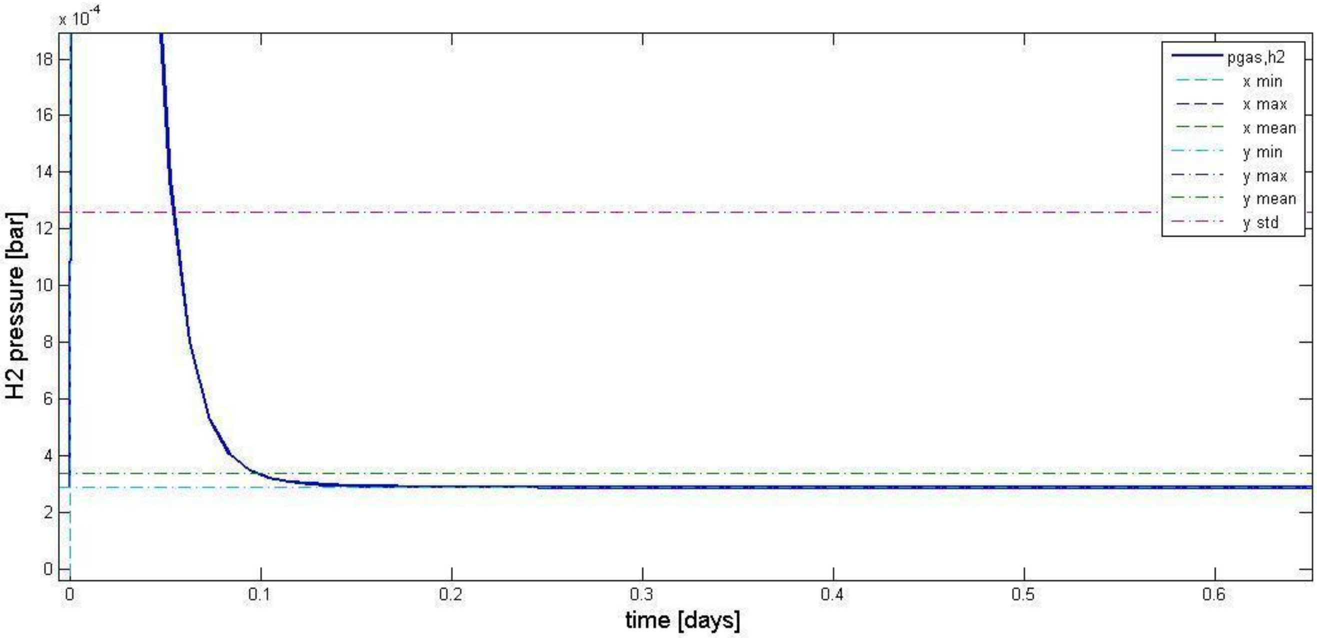


Figure 63 Simulated H_2 partial pressure (pgas,H2)

$S_{gas,CO2}$ can be deducted with the following algebraic equation Eq.138:

$$S_{gas,CO2} = \frac{R \cdot T}{p_{gas,CO_2}} \qquad (138)$$

In Figure 64 the CO_2 concentration is simulated and a value of 0.0203 [kmoleC/m^3] is reached as a maximum in the first day, after that it decreases to a constant value of 0.0185 [kmoleC/m^3] after 5-6 days.

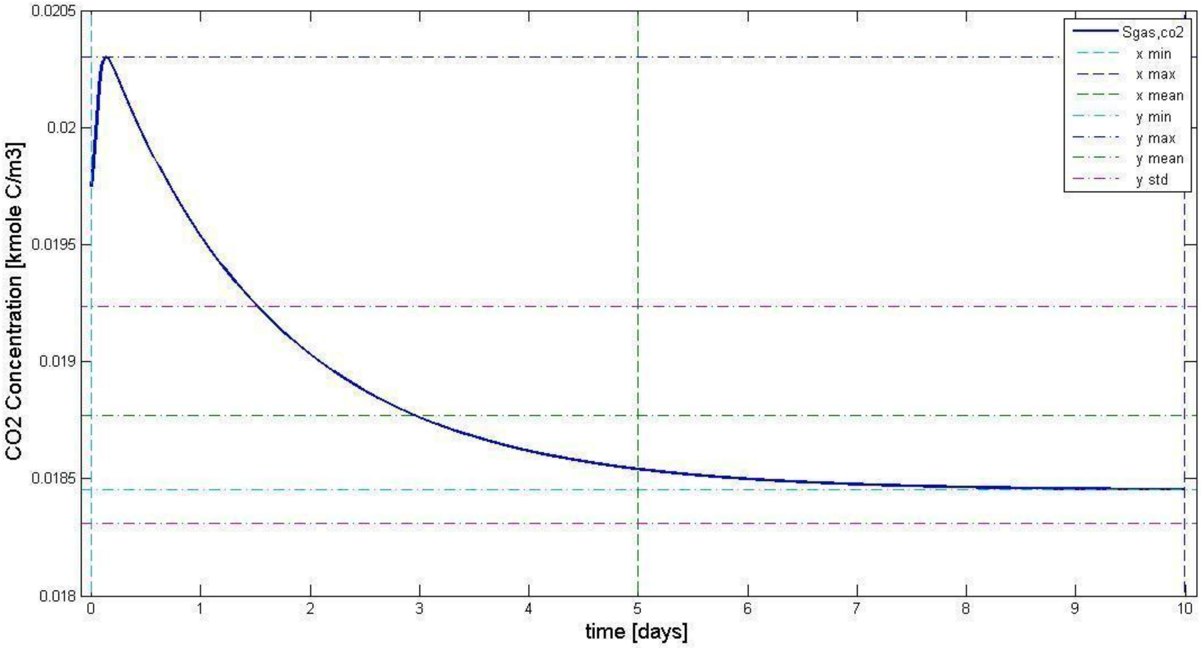


Figure 64 Simulated concentration of CO2 (Sgas,CO2)

In Figure 65 the concentration of CH_4 is simulated, which has the most important impact in the biogas quality and consequently to the electricity production. The amount of CH_4 increases to 2.83 [kgCOD/m^3] in the first day and after that it reaches a constant value of 2.975 [kgCOD/m^3].

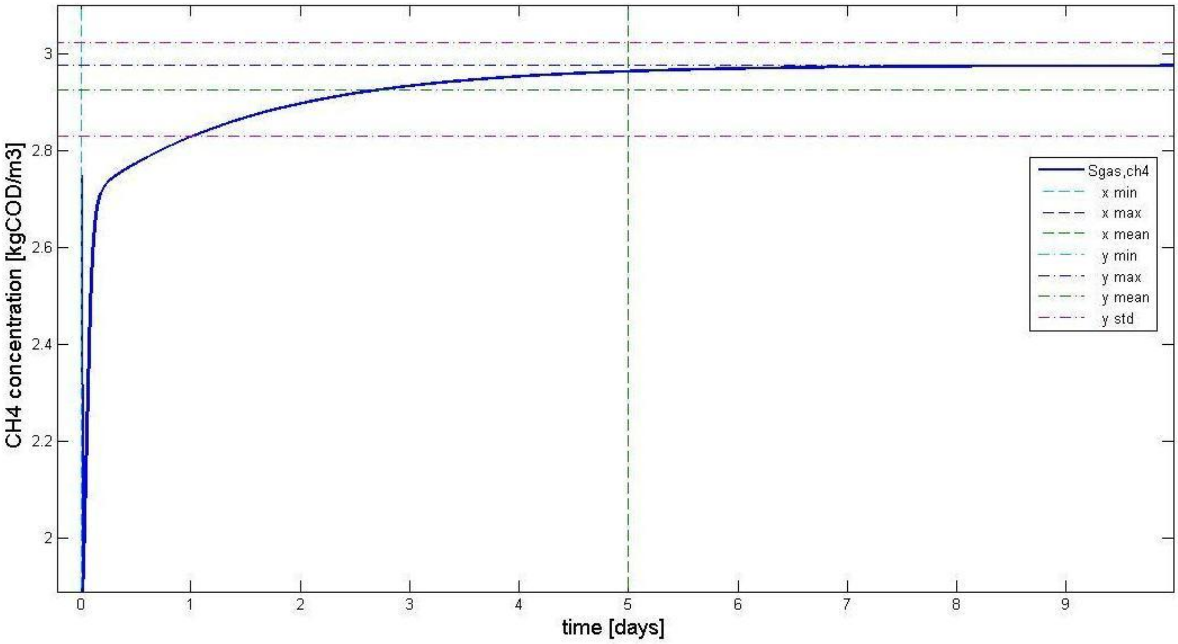


Figure 65 Simulated methane concentration (Sgas,CH4)

In Figure 66 the simulated hydrogen concentration is simulated. $S_{gas,H2}$ reaches a maximum of 0.016 [kgCOD/m^3] and decreases in the same day to 0.0001 [kgCOD/m^3], remaining constant. The low concentration of H_2 indicates a good quality of biogas in terms of calorific power.

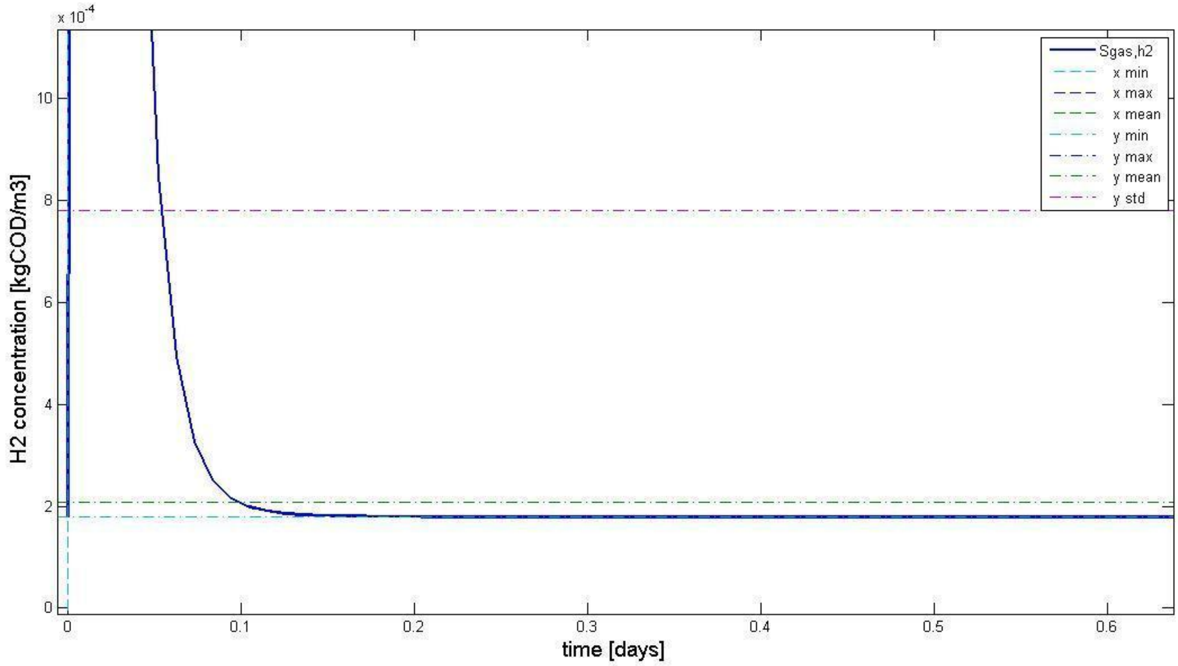


Figure 66 Simulated H2 concentration (Sgas,H2)

In the gas phase, for the biogas flow, its components and partial pressures, compared to data plant are close to what‟s happening at the plant, inside the digesters.

Though, a further calibration is needed. Simulations show that in the first day the biogas produced, biogas pressure, methane concentration, methane pressure, they increase and then they stabilize at a constant value after approximately 4-5 days.

Instead, the CO_2 gas pressure, concentration and H_2 gas pressure and concentration, reaches a maximum and decreases to a constant value after approximately 4-5 days.

This is very important information for the process control and for the plant operators. Any adjustment in the technological process, will receive a feed back only after 4-5 days.

Simulations show a good quality of the biogas, with high concentration of methane and low concentration of CO_2 and H_2. This is important for the calorific power. The higher the calorific power, the higher amount of electric energy will be produced through the CHP system. The electric energy + thermal energy produced by the CHP is used for the internal energy consumption and reduces operational costs, making the plant self-sustenaible.

Regarding the sludge composition simulations after the AD, the following results have been found below. The most important components found into the digested sludge are in descending order:

1. X_I particulate inerts (kg COD/m3)
2. S_{ac} total acetate (kg COD/m3)
3. X_{aa} amino acid degraders (kg COD/m3)
4. X_{c4} valerate and butyrate degraders (kg COD/m3)
5. X_{H2} hydrogen degraders (kg COD/m3)
6. X_{SU} sugar degraders (kg COD/m3)
7. X_{fa} LCFA degraders (kg COD/m3)
8. S_{fa} long chain fatty acids (LCFA) (kg COD/m3) (soluble/liquid form)
9. X_{pro} propionate degraders (kg COD/m3)
10. X_{pr} proteins (kg COD/m3)
11. X_{xc} composites (kg COD/m3)
12. S_{cat+} cations (metallic ions, strong base) (kmole/m3)
13. S_{ch4} methane (kg COD/m3)
14. S_{pro} total propionate (kg COD/m3)

15. X_{ch} carbohydrates (kg COD/m3)

S_{aa}, S_{va}, S_{bu}, S_{IN}, S_{IC}, X_{li}, X_{ac}, S_{an} have very slight variations and the lowest values. Sludge composition data cannot be compared with plant data and calibrated.

If compared to literature data (mainly Batstone, 2002), simulation sludge composition data is close to literature data. Further calibration is needed.

Nonetheless, these simulations offer some valuable information for the plant operators about the „black-box‟ process in AD with respect to the mesophilic digesters.

In Figure 67 the particulate inerts, X_I are represented. They have a significant constant value of 31.775 kgCOD/m^3. The variations are almost negligent. According to Schon M., 2010, X_I is a single compound that comprises both inert products of disintegration process and inert products of disintegration process and inert decay products, although these processes are not coupled and produce particles with different nitrogen content. X_I needs to be calibrated to the final ammonia concentration in the digester (released nitrogen). This parameter also offers information about the settleability of the sludge.

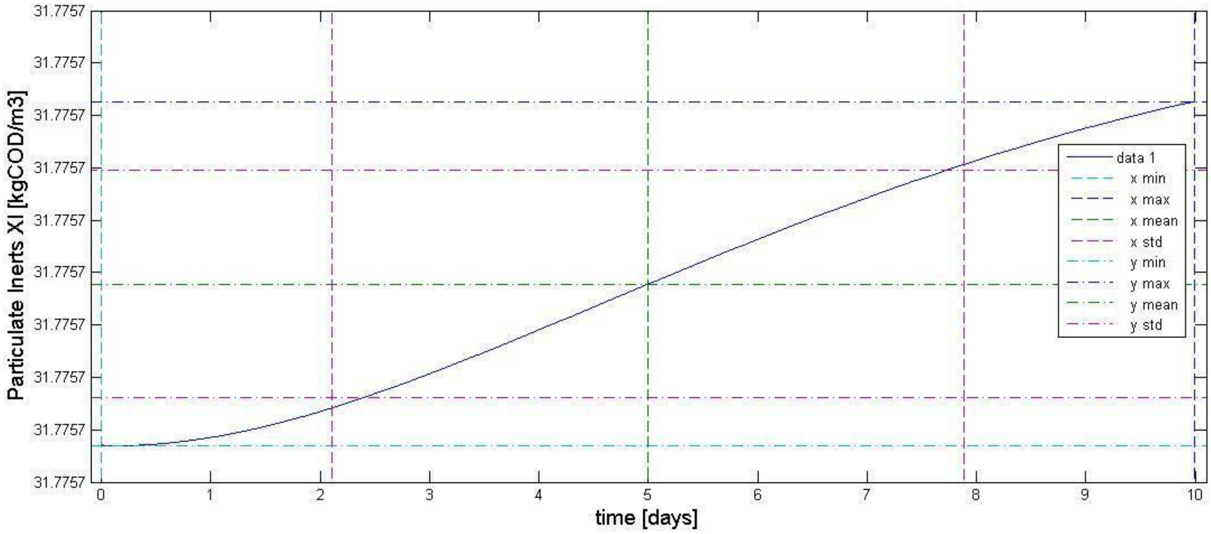


Figure 67 Simulations of particulate inerts in time

In Figure 68 the total acetate is simulated at a minimum value of 24.6405 kgCOD/m3 in the first day and increases slightly to a constant value of 24.6425 kgCOD/m3, after approximately 6 days.

The high total acetate in the liquid phase, shows information about the acetogenesis phase from butyrate and valerate, which has an inhibition effect because of the lower value of acetate degrader (X_{ac}). The acetate has influence over the pH inside the digesters, which acidifies it.

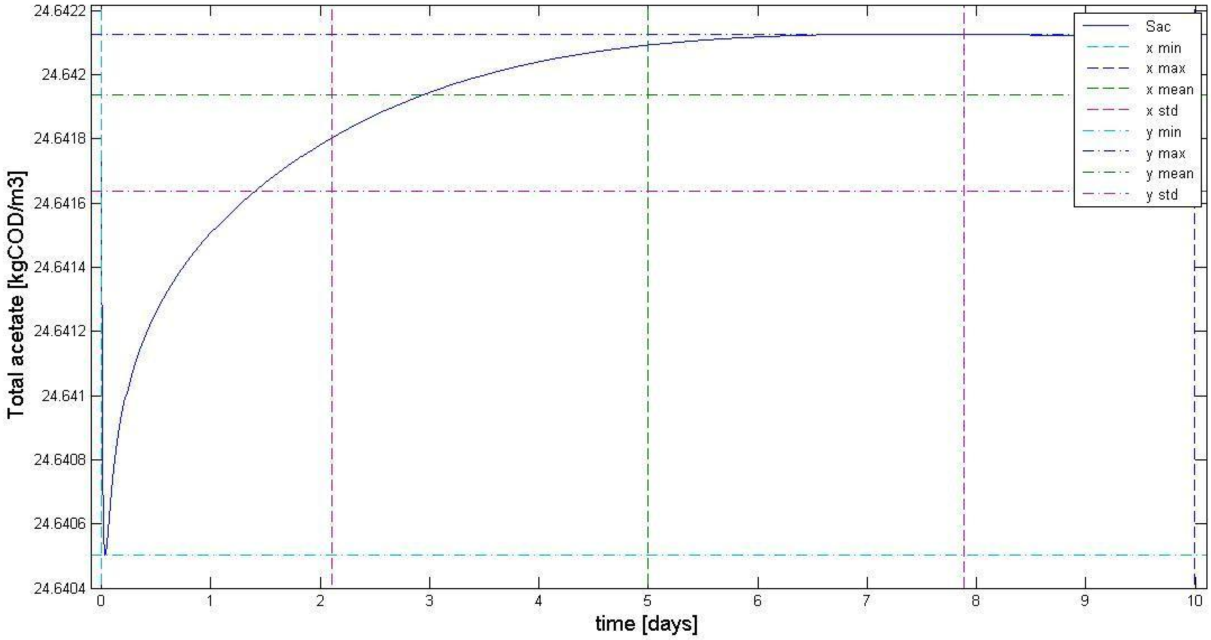


Figure 68 Simulations of total acetate in time

In Figure 69 the amino acids degraders are presented. The variations are very low; X_{aa} is at a constant value of 1.455 kgCODm^3. The proteins are well disintegrated by the amino acids degraders in the acidogenesis step, because the amino acids (S_{aa}) have lower values.

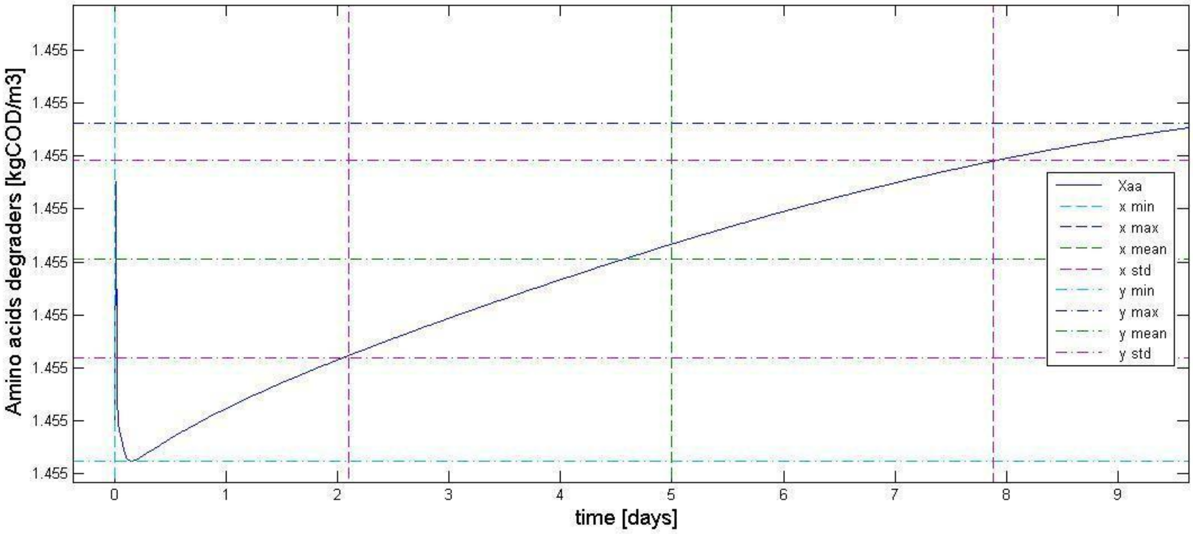


Figure 69 Simulations of amino acids degraders in time

In Figure 70, the valerate and butyrate degraders are represented. X_{c4} varies slightly and reaches a constant value of 0.5073 kgCOD/m^3. The valerate and butyrate in the liquid phase (S_{va} and S_{bu}), lower values show a good transformation to acetate and hydrogen from the acetogenesis phase.

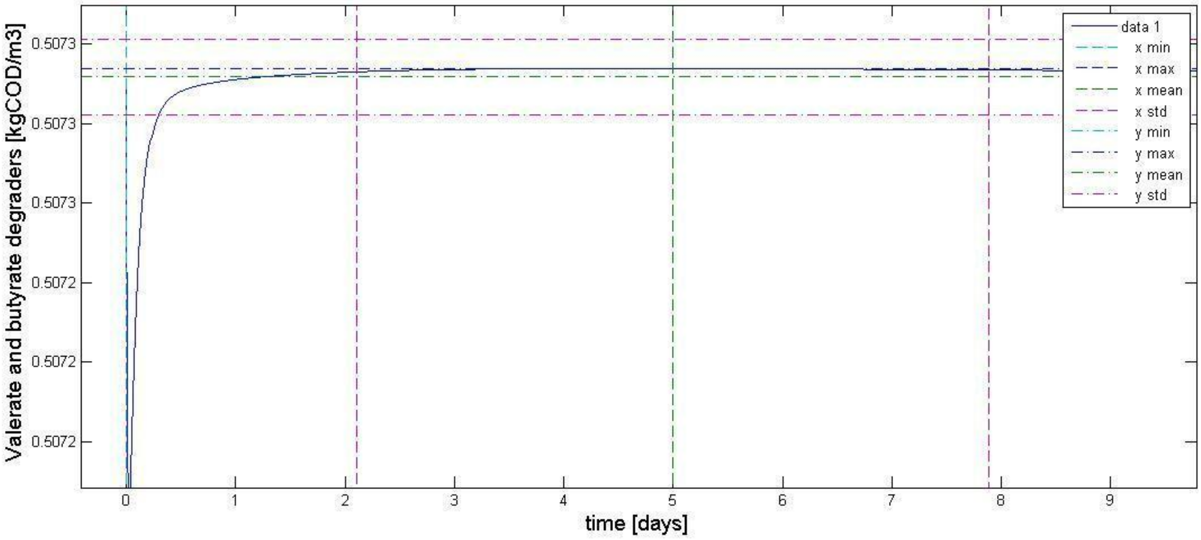


Figure 70 Simulations of valerate and butyrate degraders

In Figure 71 the hydrogen degraders are represented. The values vary slightly as well. It reaches a maximum 0.3114 kgCOD/m^3 and then afterwards decreases to 0.3112 kgCOD/m^3. The higher value means that the hydrogenotrophic methanogenesis is taking place in good conditions, which means a good production of methane and carbon dioxide.

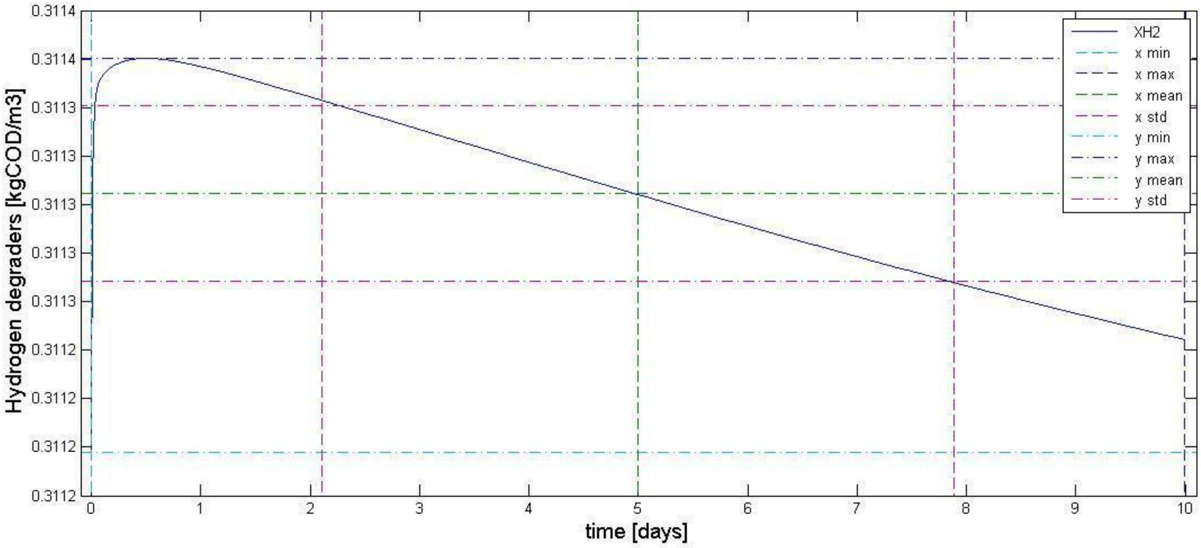


Figure 71 Simulations of hydrogen degraders in time

In Figure 72 the sugar degraders are represented. X_{su} slighty varies. It slightly decreases and increases to a value of 0.2373 kgCOD/m^3. X_{su} offers information about the acidogenesis from sugars phase. In this case the sugars are well disintegrated in propionate because of lower S_{pro} value.

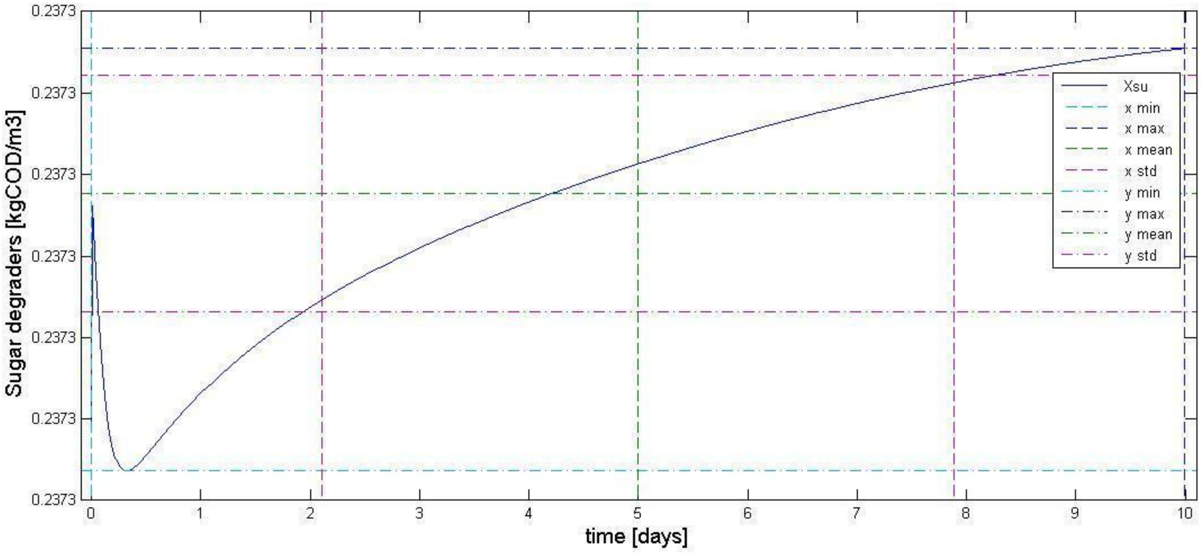


Figure 72 Simulations of sugar degraders in time

In Figure 73 the LCFA degraders are represented. There is a slight variation. The constant value of X_{fa} reaches 0.2045 kgCOD/m^3. This shows a good, or normal acetogenesis from LCFA and lipid disintegration, because lower value of S_{fa}.

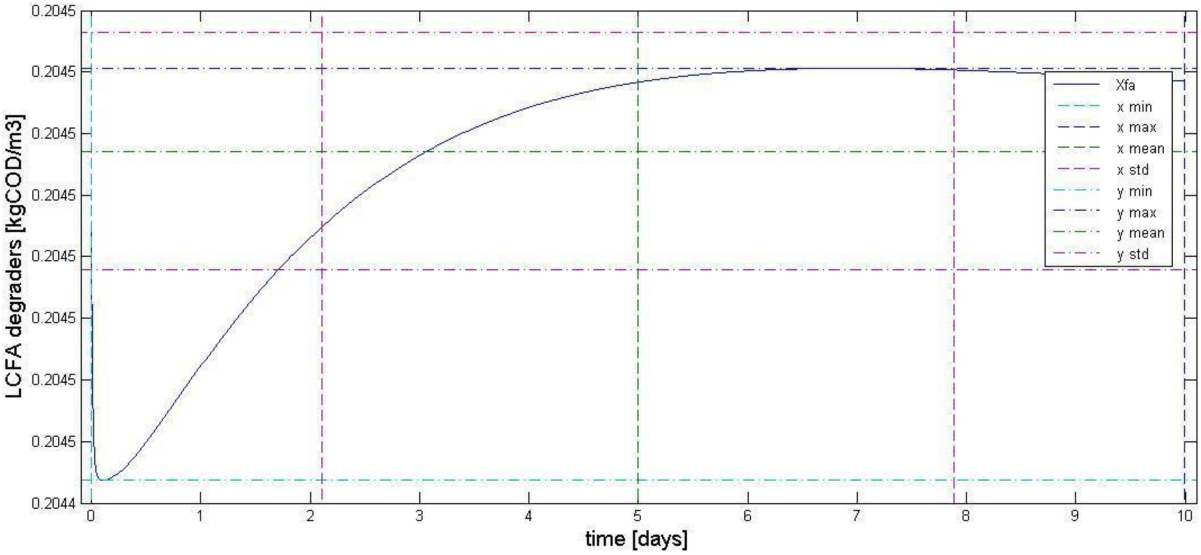


Figure 73 Simulations of LCFA degraders in time

In Figure 74 the long chain fatty acids from the liquid phase, are presented. The lower value of S_{fa} than X_{fa} means a normal acetogenesis from LCFA and lipid hydrolysis.

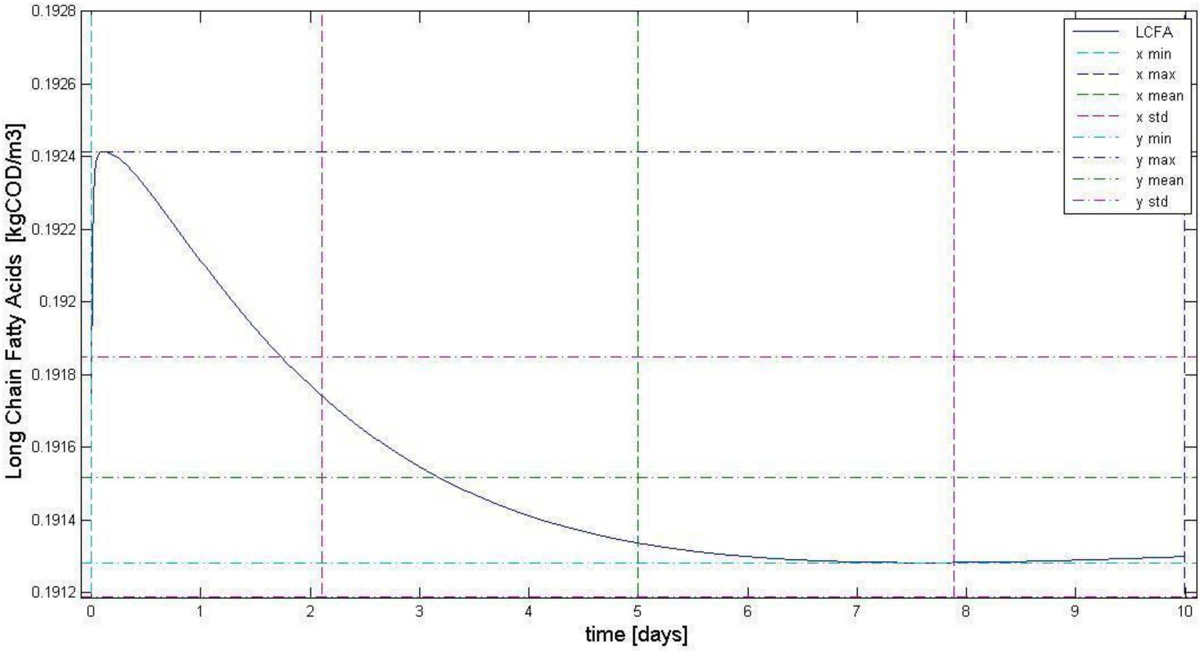


Figure 74 Simulations of long chain fatty acids in time

In Figure 75 the propionate degraders are represented. There are slight variations. The constant values reaches 0.1335 kgCOD/m^3. Higher value of X_{pro} than S_{pro} means a good or normal acetogenesis from propionate.

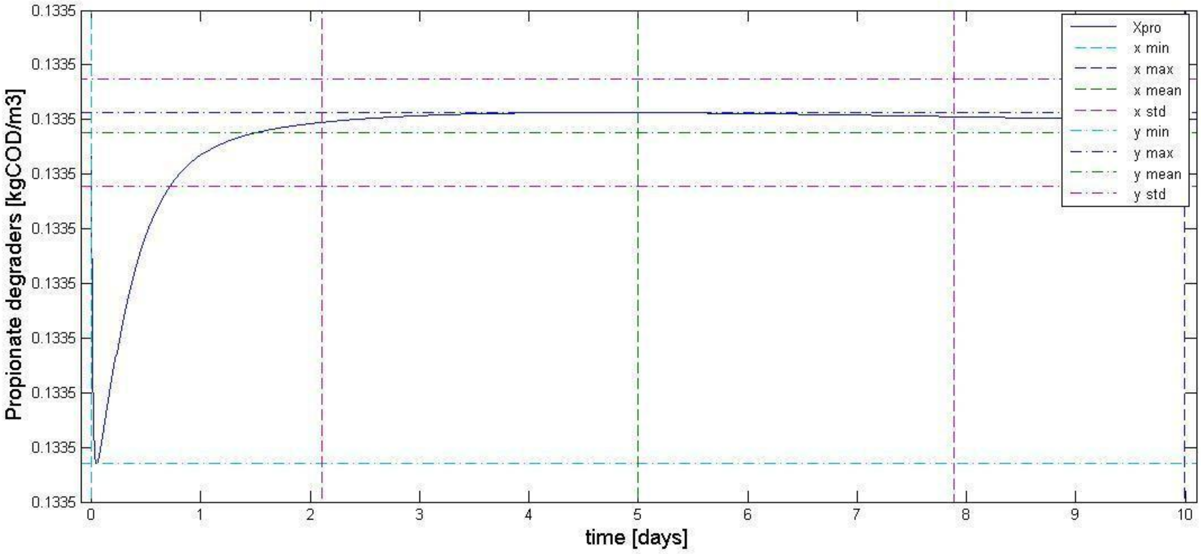


Figure 75 Simulations of propionate degraders

In Figure 76 the proteins degraders are represented. It has a constant value of 0.1064 kgCOD/m^3. Higher value of X_{pr} than S_{aa} means a normal acidogenesis phase from amino acids.

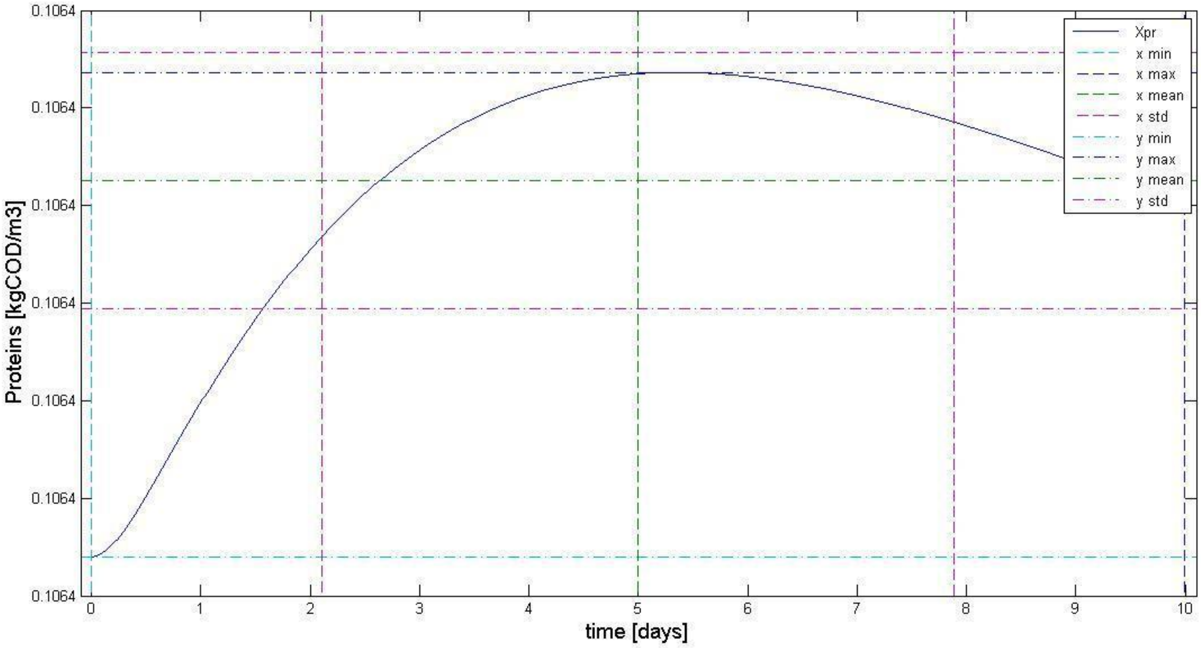


Figure 76 Simulations of proteins in time

In Figure 77 the composites are represented. X_{xc} has a constant value of 0.1058 kgCOD/m^3. X_{xc} is subject to a disintegration process before it's hydrolysis. It consists of particulate subject of disintegration and products of biomass decay.

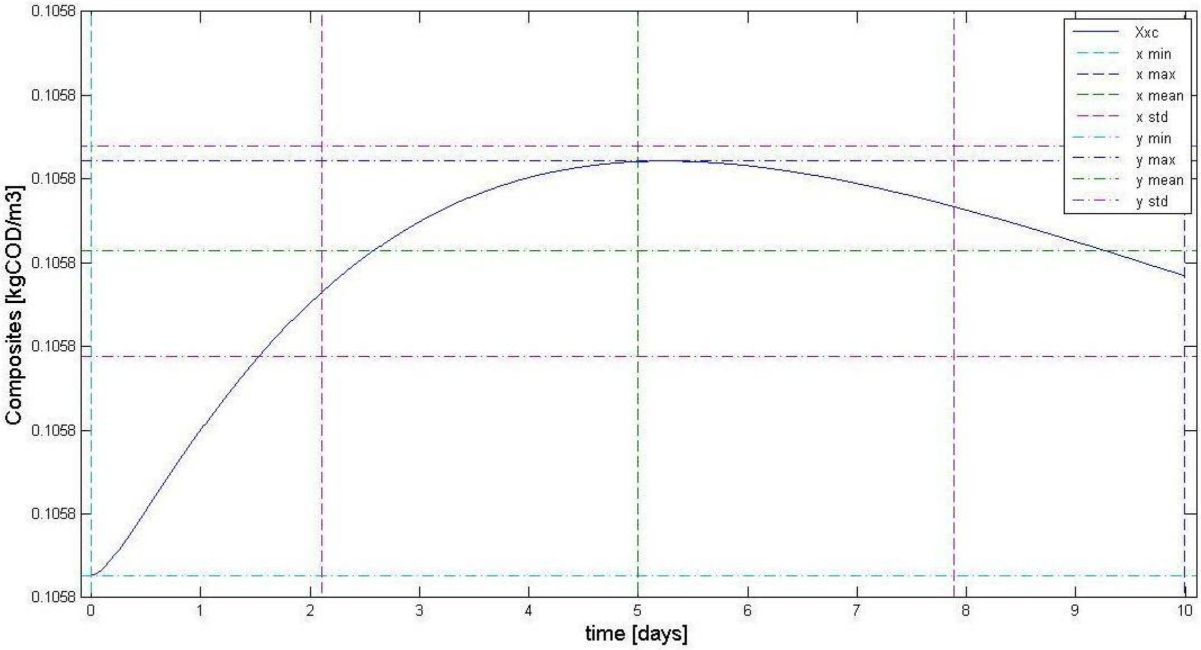


Figure 77 Simulations of Composites in time

In Figure 78 the cations are represented. S_{cat+} has a constant value of 0.1019 kgCOD/m^3. S_{cat+} includes metallic ions such as Na$^+$ and is included to represent strong bases. S_{cat+} is 12 times lower than S_{an-} which means that the output sludge composition inside the digesters has a acidic trend.

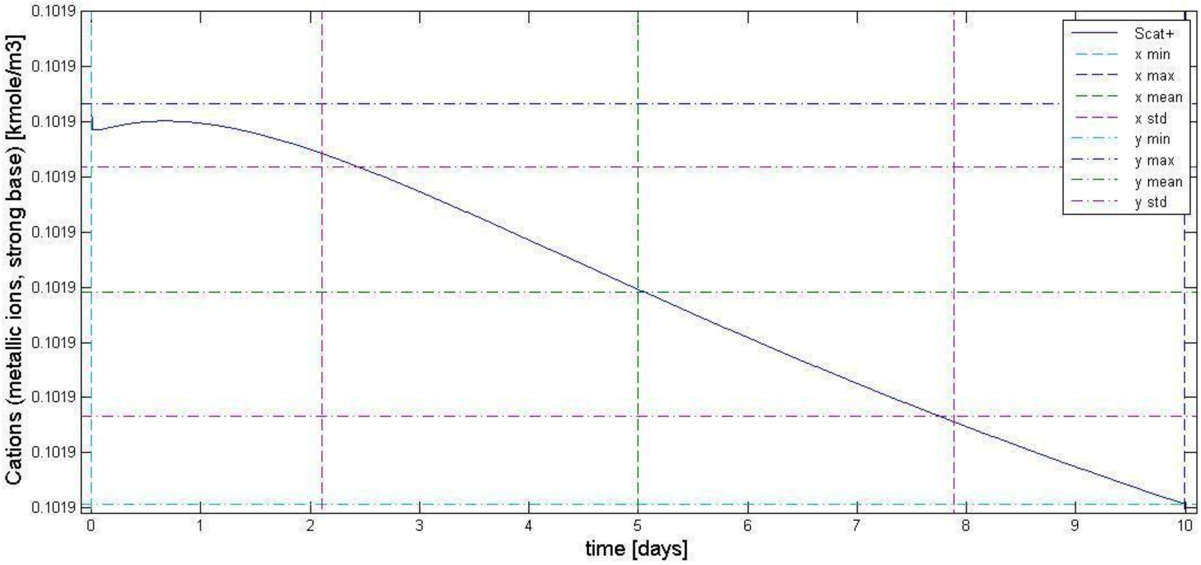


Figure 78 Simulations of cations (metallic ions, strong base) in time

In Figure 79 the methane in the liquid form is presented. The S_{ch4} slightly varies. It has a constant value of 0.03827 kgCOD/m^3. The CH_4 liquid phase transfer has the following rate equation for liquid-gas reaction Eq.139:

$$k_La(S_{liq,CH4} - 64 \cdot K_{H,CH4} \cdot p_{gas,CH4}) \qquad (139)$$

where:

k_La - gas-liquid transfer coefficient [d^{-1}]

$K_{H,CH4}$ – Henry’s law coefficient [M bar^{-1}]

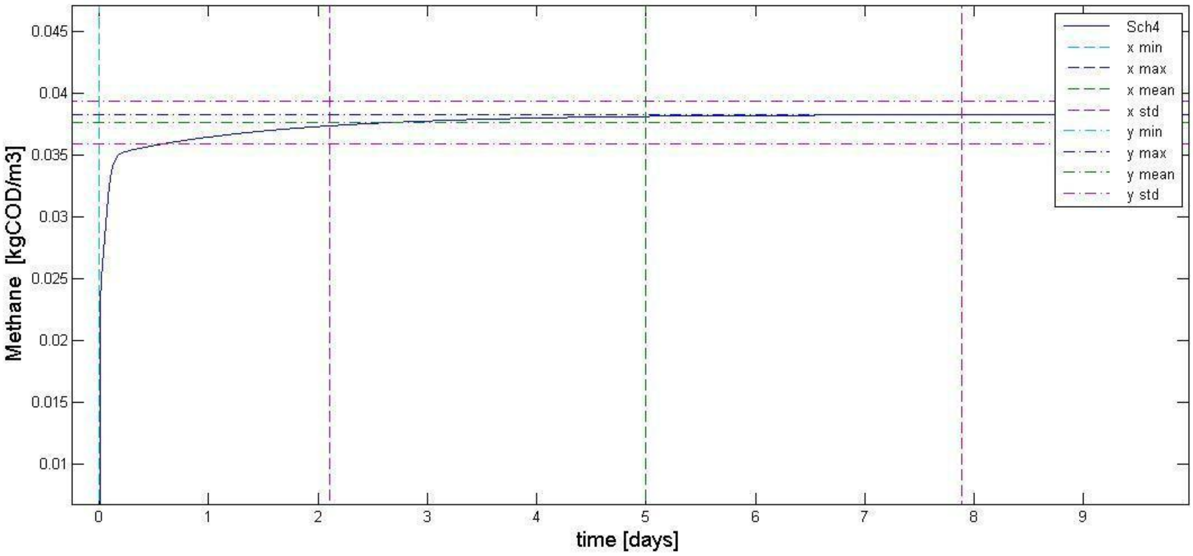


Figure 79 Simulations of methane (soluble/liq) in time

In Figure 80 the total propionate is represented. S_{pro} increases up to 0.0365 kgCOD/m^3 and then decreases after approximately 2 days at 0.0358 kgCOD/m^3. S_{pro} is 4 times lower than X_{pro}, which means good acetogenesis from propionate. Propionate is an intermediary component to acetate.

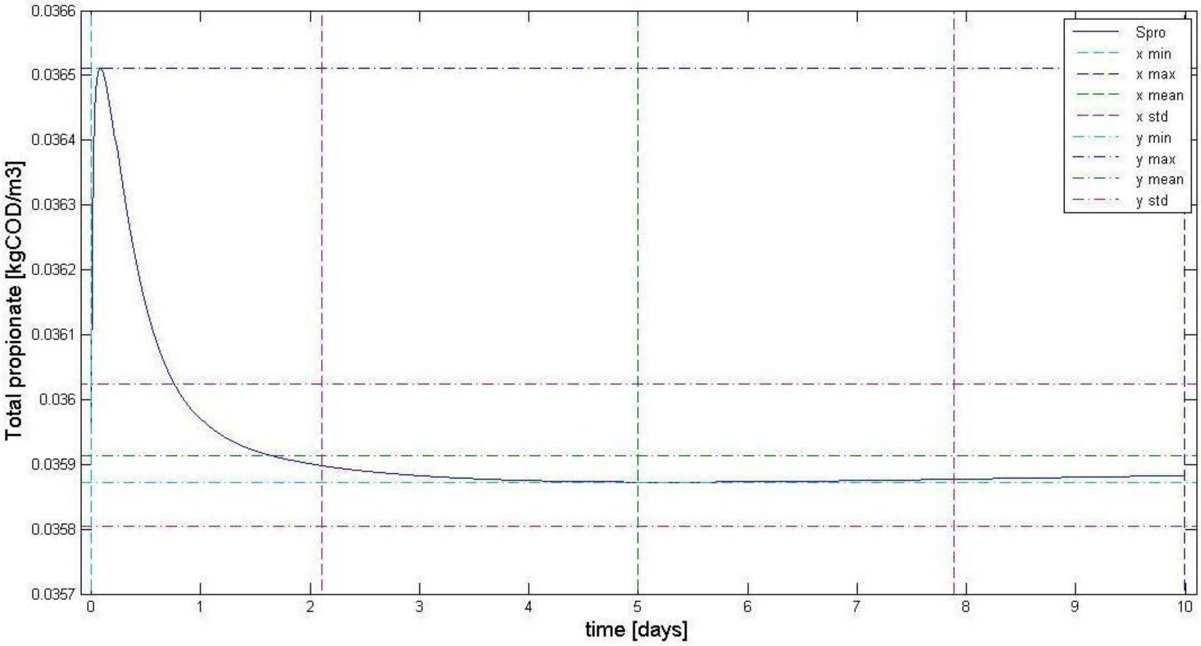


Figure 80 Simulations of total propionate in time

In Figure 81 the carbohydrates degraders are represented. The X_{ch} has a constant value of 0.0129 kgCOD/m^3. X_{ch} degrade the carbohydrates into sugars (S_{su}) through hydrolysis step.

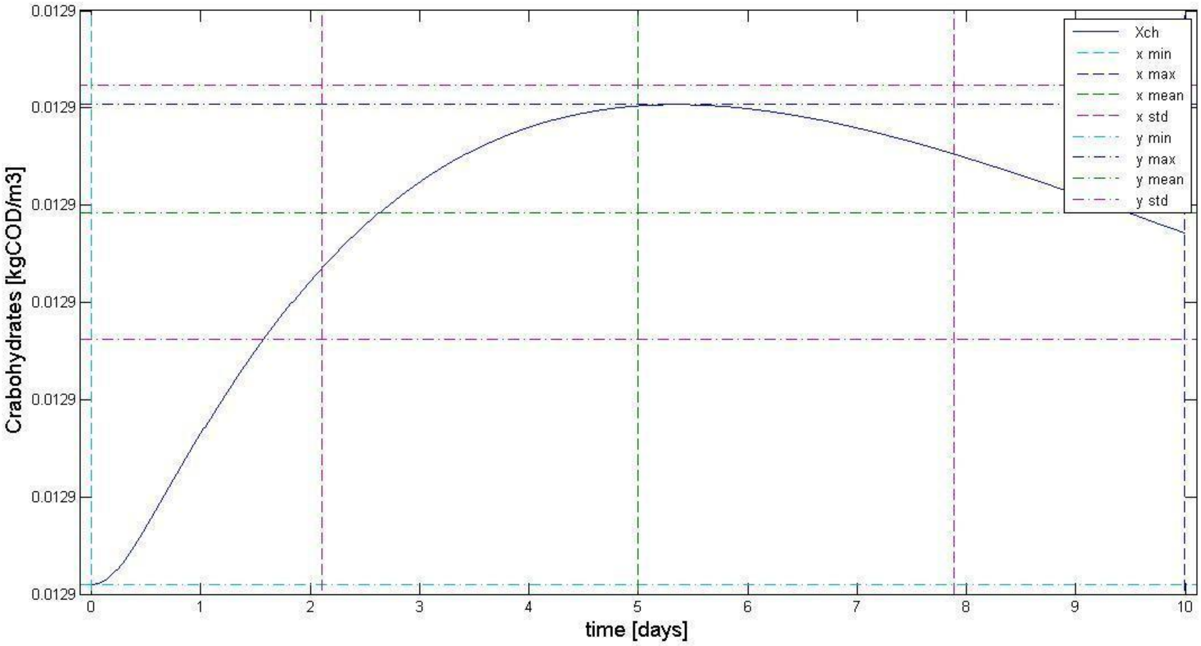


Figure 81 Simulations of carbohydrates in time

Conclusions

Simulations show that the major gas phase parameters: qgas (Nm^3/day), $S_{gas,CH4}$ (kgCOD/m^3), $S_{gas,CO2}$ (kmole C/m^3), $S_{gas,H2}$ (kgCOD/m^3), p_{gas} (bar),p_{CH4} (bar), p_{CO2} (bar), and p_{H2} (bar) are very close to Cluj-Napoca WWTP data.

All the sludge output compositions in descending order, such as: X_I particulate inerts (kg COD/ m^3), S_{ac} total acetate (kg COD/ m^3), X_{aa} amino acid degraders (kg COD/ m^3), X_{c4} valerate and butyrate degraders (kg COD/ m^3), X_{H2} hydrogen degraders (kg COD/ m^3), X_{SU} sugar degraders (kg COD/ m^3), X_{fa} LCFA degraders (kg COD/ m^3), S_{fa} long chain fatty acids (LCFA) (kg COD/ m^3) (soluble/liquid form), X_{pro} propionate degraders (kg COD/ m^3), X_{pr} proteins (kg COD/ m^3), X_{xc} composites (kg COD/ m^3), S_{cat+} cations (metallic ions, strong base) (kmole/ m^3), S_{ch4} methane (kg COD/ m^3), S_{pro} total propionate (kg COD/ m^3), X_{ch} carbohydrates (kg COD/ m^3), fit with the literature data.

The simulations show high values of particulate inerts, total acetate and amino acid degraders, which reveals an acid trend into the sludge composition.

ADM1 is mainly based on sludge composition parameters so that, introducing a proper monitoring of VFAs would be very useful for data consistency so that it can be calibrated to plant data.

However for both gas-phase parameters with respect to biogas production and also the sludge output compositions parameters needs to be calibrated, so that the model could be further optimized. The optimized model could be a valuable tool in the control of the AD process, for the sludge line treatment and biogas production.

Conclusions and further work perspective

The objective of the thesis was to increase the level of understanding of anaerobic digestion process and apply a structured anaerobic digestion model at Cluj-Napoca WWTP. ADM1 has been adapted to Cluj-Napoca secondary sludge line treatment for anaerobic digestion, using industrial plant data.

After recent rehabilitation of the plant, the optimization of the process control is still in progress up to date. All adjustments made for wastewater line improvement, which is the primary purpose of the plant have resulted in some fluctuations on the sludge line which is a secondary technological process.

Simulations have shown a relatively good fit with plant data, regarding the biogas flow and its components and biogas pressure with its respective partial pressures. The main simulation parameters regarding sludge composition are in agreement with literature sludge composition parameters. Process monitoring of acids spectrum in terms of VFA, possible analysis methods and instrumentation has been proposed for a better process control. Calibration, validation and optimization of the model could be further conducted in order to develop a practical tool for Cluj-Napoca plant operators.

The research performed serves as a guideline for plant operators on sludge line in controlling anaerobic digestion process. Simulations have shown valuable information about bio-chemical reaction structure, kinetics and physico-chemical interactions. Regarding process control aspects, it has been found that for any adjustment performed on the anaerobic digestion process, will receive a relevant and consistent feedback only after approximately 4-5 days after the process starts to stabilize to constant values. Researchers and practitioners can use the results for design, analysis and optimization of anaerobic digestion.

To obtain self-sustainability at Cluj-Napoca WWTP, an energy efficiency and techno-economical investigation of anaerobic digestion technology for the CHP co-generation system, has been performed, to detect maximum methane concentrations in biogas production and minimize the costs at Cluj-Napoca WWTP.

Biogas augmentation methods have been proposed as well as for the feedstock input composition through the co-digestion process. A successful study-case has been investigated for co-digestion process at Budapest South-Pest WWTP. Co-digestion might be considered as a future option for Cluj-Napoca WWTP for biogas augmentation and plant sustainability.

I hope that this thesis will be of service to the community of engineers and researchers working in anaerobic digestion and degradation processes and that it will promote further optimization and process control perspective.

Personal contributions

Starting from the thesis's objective to model and simulate the meshophilic anaerobic digesters for biogas production, the most commonly used mathematical model ADM1, has been adapted to Cluj-Napoca Wastewater Treatment Plant data. Heat exchangers for heating the sludge to the mesophilic anaerobic digestion and recirculation of biogas for mixing purposes have been integrated into the model. Simulation results show complex biochemical and physico-chemical interactions and represent a comprehensive guide in process optimization and control for plant operators.

The process monitoring on sludge line, which is a secondary technological process at Cluj-Napoca WWTP has been observed and various methods for acids spectrum identification has been suggested for later sludge composition data calibration.

Foam bulking through short term and long-term methods have been tested and analyzed for Sofia Kubratovo WWTP in re-establishing a healthy sludge for digestion, which bring contributions to other specialists in the field that are confronting with such problems.

A sensitivity analysis has been performed to determine the major process parameters that influence the biogas formation and to show correlation between the sludge composition parameters.

A techno-economical analysis of CHP was carried out for the energy efficiency of the plant, to determine maximum concentrations of methane and minimum operational costs, in order to achieve self-sustainability.

Solutions for biogas augmentation have been discussed and co-digestion has been proposed to increase biogas production, due to changes in feedstock composition.

A co-digestion case study has been investigated during international mobility at South-Pest WWTP for the demonstrated benefits of termophilic anaerobic digestion of solid organic waste, added to mesophilic anaerobic digestion, in the production of biogas.

The thesis represents a first step in understanding the complex biochemical and physico-chemical interactions in mesophilic anaerobic digesters during anaerobic digestion and brings valuable contribution in process optimization and control for both plant operators and research community. Results are close to industrial data available on sludge line and are partially correlated with literature and industrial Cluj-Napoca WWTP data, but further calibration and model validation is needed, with the purpose of creating a universal, reliable and powerful tool in process control.

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