

Environmental Analysis of Wastewater Treatment Plants Control Strategies

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Abstract—In this paper the environmental impacts of 10 control strategies implemented in the Benchmark Simulation Model No. 1 (BSM1) are evaluated by using Life Cycle Analysis (LCA). The aim is to analyze their environmental profiles in order to identify the main flows contributors to those impacts and to find the existing correlations between the control strategies and the selected impact categories. The knowledge of these correlations allows to assess where are located the main environmental impacts product of the plant's operation under the control strategies evaluated and to take actions in order to reduce them.

I. INTRODUCTION

The growing of cities and industry during the last centuries brings in parallel an increase in water consumption for different human needs like drinking, cleaning, washing and for the production of goods, increasing the generation of wastes. A large part of them are discharged to the rivers and oceans, which have every time less capacity to dilute wastes, affecting the surrounding ecosystems and also to the human beings themselves.

Wastewater Treatment Plants (WWTPs) have the function of remove the pollutants from wastewater before its discharge into the rivers and oceans. The water providing from urban use and certain industries sectors is collected and transported to WWTPs and then a pretreatment is applied to separate the floating solids, the sand, grease and less dense liquids from wastewater. After, a primary treatment, consisting of a primary decantation, is applied to reduce the suspended solids that can not be separated in the pretreatment. Then, secondary treatments like activated sludge, extended aeration and so on, are used to remove the dissolved pollutants. Among those treatments, one the most used nowadays is the activated sludge, where biological treatments like denitrification and nitrification take place in the plant's reactors. After, a secondary decantation separates the treated water from sludge, which is discharged in the natural courses. The generated sludge is treated by using processes like thermal drying, lime treatment, anaerobic digestion and so on to condition it before its final use. Then, it is used as a fertilizer, replacing

chemical ones by avoiding their production, as a compost in agriculture, as fuel in cement plants, or simply disposed of in landfill.

Life Cycle Analysis (LCA) is considered as an useful tool for assessing the environmental performance of WWTPs [1], [2], [3]. LCA has been defined, according to [4], as a technique for assessing the environmental aspects and potential impacts associated with a product/process/service. The analysis is done by compiling an inventory of the most relevant input and outputs of the system, evaluating the potential impacts associated with these inputs and outputs and interpreting the results of the inventory analysis and impact assessments phases in relation to the objectives of the study [5]. This means that the study includes, besides the product/process fabrication, the extraction of raw materials needed, its use, maintenance, and the waste management after its useful life has finished.

In this work the environmental profile 10 control strategies performed in the benchmark simulation model No. 1 (BSM1) platform is analyzed by using the LCA methodology. The objectives are to analyze the environmental profiles of the strategies in order to identify the main contributors to the environmental impacts and to find the correlations between the control strategies and the impact categories.

II. CONTROL SIMULATIONS

A. The BSM1 plant description

The BSM1 plant is composed of 5 activated sludge reactors in series followed by a clarifier. The first two reactors are non aerated but fully mixed tanks with a total volume of 2000 m^3 . They are followed by 3 aerobic tanks with a total volume of 3999 m^3 and the clarifier has a total volume of 6000 m^3 (fig. 1). The plant has been designed to treat an average influent dry-weather flow rate of $18466\text{ m}^3\text{d}^{-1}$ and an average biodegradable of Chemical Oxygen Demand (COD) in influent of 300 gm^{-3} . The hydraulic retention time is of 14.4 hrs and the wastage flow rate (Q_w) is of $385\text{ m}^3\text{d}^{-1}$ [6]. The models used for describing the processes that take place in the sludge reactors and the clarifier are the Activated Sludge Model No. 1 (ASM1) [7] and the Takács Model [8] respectively. More detailed explanation about the BSM1 plant can be found in [6].

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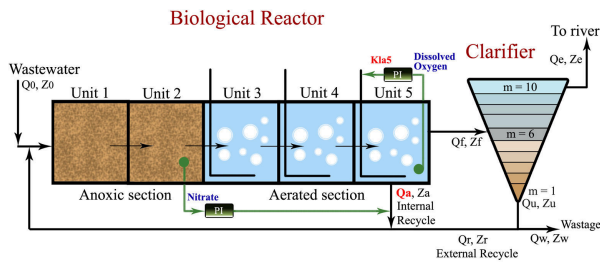


Fig. 1: BSM1 plant layout

B. Control strategies implemented

A set of 5 basic control strategies (S1 to S5) has been implemented by using the following control loops respectively:

- Control of the dissolved oxygen concentration (D_O) in the aerobic reactors by manipulating its respective oxygen transfer coefficients ($K_L a$).
- Control of the ammonia (S_{NH}) in the effluent by manipulating the D_O set points in all the aerobic tanks.
- Control of the nitrates concentration (S_{NO}) by manipulating the internal recycle flow rate (Q_a).
- Control of the nitrates concentration (S_{NO}) by manipulating the carbon source flow rate (Q_{Carb}) into the unit 1.
- Control of the total suspended solids concentration (T_{SS}) in last aerobic tank by manipulating the wastage sludge flow rate (Q_w).

Then, by combining these basic strategies, the strategies S6 to S10 have been implemented. The details of all control strategies are summarized in table I.

III. LIFE CYCLE ASSESSMENT

The LCA study has been performed according to the 4 main phases normally considered: goal and scope, inventory analysis, impact assessment and interpretation of the results.

A. Goal and scope definitions

1) *Objective*: The main objective of this study is to analyze the environmental profile of 10 control strategies implemented in the BSM1 plant and to find the correlations between those control strategies and the impact categories selected.

2) *Functional unit*: The functional unit (FU) is the unit at which are referred all inventory data (inputs and outputs). The definition of the FU is done starting from the definition of the system function because it is the base for comparison and will affect the results of the study [13]. Thus, referring this unit to the average influent dry-weather flow rate ($18466 \text{ m}^3 \text{d}^{-1}$) and its corresponding loads, it has been selected as FU the treatment of 1 m^3 of

wastewater during 7 days, that is the observation time for the BSM1.

3) *System boundaries*: As the aim is to compare the impact of different control strategies, system boundaries have been established from “gate to gate” of the BSM1 WWTP. The construction stage of the WWTP has not been taken into account because it does not affects the comparative results (is the same plant for all control strategies). However, it has been included into the boundaries the generation and transmission of the electricity used in the plant, the production of the chemicals used in the anoxic reactors to improve denitrification and the transportation of the sludge generated to its final destination. The sludge generated is considered that is used in agriculture as a fertilizer, been this application one of the most common in Spain [1].

B. Inventory analysis

The inventory analysis phase consists of data collection and analysis of the system under study in order to quantify the inputs and outputs. The inputs and outputs are related to the use of resources (energy and raw materials) and to the release of emissions to soil, waters and air.

The major part of data for this study was collected from the dynamic simulations performed using the BSM1. Table II shows the inventory data parameters used in this LCA study for each one of the control strategies implemented referred to the functional unit.

However, some part of the inventory data needed to perform the LCA was not provided by the simulations and was collected from databases and literature such as:

- **Electricity and chemicals**: The electricity production data were taken from Ecoinvent Database taking into account the Spanish energy production profile. In the case of the chemicals used in the BSM1 plant, it has been selected the methanol as the external carbon source for enhancing the denitrification process [14].
- **Fertilizers avoided**: The application of sludge in agriculture avoid the use of chemical fertilizers. This use results in benefits for the soil as long as the concentration of heavy metals in the sludge is within the permitted limits [15]. The most common chemical fertilizers used in Europe are the calcium ammonium nitrate (N-based) and the triple superphosphate (P-based) [16]. The substitutability was assumed as 6.93 kg of triple superphosphate and 39.6 kg of calcium ammonium nitrate per ton of sludge [1].
- **Heavy metals in the sludge**: Heavy metals concentration depends strongly of the amount of industrial wastewaters in the influent flow. As the influent used does not contains measures of these concentrations, as a source, it has been selected the study realized in several European countries that summarizes the average of heavy metals concentrations that can be found in dehydrated sludge [15].

TABLE I: Description of the control strategies implemented

Characteristics	3 D_O controller	S_{NH} cascade controller	Q_a controller	Q_{carb} controller	T_{SS} controller
Measured variable (s)	D_O in Units 3, 4 and 5	S_{NH} in Unit 5	S_{NO} in Unit 2	S_{NO} in Unit 2	T_{SS} in Unit 5
Controlled variable (s)	D_O in Units 3, 4 and 5 2, 2 and 2	S_{NH} in Unit 5	S_{NO} in Unit 2	S_{NO} in Unit 2	T_{SS} in Unit 5
Set point (gm^{-3})	(variable in S_{NH} cascade controller)	1	1	1	4000
Manipulated variable (s)	$K_L a$ in Units 3, 4 and 5	D_O set point in 3 D_O controller	Q_a	Q_{carb} in Unit 1	Q_w
Control algorithm	PI	Cascade PI	PI	PI	PI
Used in control strategy	S1, S2, S6, S7 S8, S9 and S10	S2, S6, S7 S8, S9 and S10	S3, S6 and S10	S4, S7 and S9	S5, S8, S9 and S10
Reference	[6]	[9]	[10]	[11]	[12]

- **Methane and nitrogen emissions:** The emissions resulting from the sludge application to agriculture was calculated as in [17] and [18].
- **Phosphorous:** As the ASM1 does not takes into account the phosphorus removal process, the phosphorous concentration in the effluent was not considered.
- **Sludge transportation:** The transportation of sludge to the farms for agricultural purposes has been calculated by supposing that farms are located at 35 km from the WWTP. Data for the calculation of the environmental loads caused by the sludge transportation in a 16 ton lorry has been taken from [14].

C. Impact assessment

In this phase of the LCA, the inputs and outputs of the inventory are analyzed and their respective potential contributions are cataloged in terms of several impact categories. The result of the Life Cycle Impact Assessment (LCIA) is an evaluation of the product life cycle, established by the relationships between the use of resources and the release emissions, to their respective impacts.

In this study it has been used the CML 2000 methodology, developed by the Institute of Environmental Sciences (CML) of Leiden University [19], to analyze the operational impact of strategies implemented. This methodology quantifies in a single score the impact for each category. From a wide set of impact categories available, a set of 7, have been selected to perform this study taking into account that they are commonly used in wastewaters LCA studies [1], [2].

The impact categories are:

- Acidification potential (AP).
- Global Warming potential (GWP).
- Eutrophication potential (EP).
- Photochemical Oxidation potential (PHO).
- Depletion of abiotic resources potential (DAR).
- Ozone layer depletion potential (ODP).
- Terrestrial ecotoxicity potential (TAETP).

D. Interpretation of the results

In this phase, inventory data and results of the impact assessment carried out, are evaluated in order to identify the critical sources of impact, the main flows contribution and the impacts of the strategies performed with the objective of suggest actions for improving the performance of the plant from the environmental point of view.

IV. RESULTS

A. Main flows contribution to the impacts

From the impact assessment analysis it has been found that electricity consumption is the major contributor to the GWP (between 70-84 % of total impact), DAR (78-99 %), ozone layer depletion (77-98 %), PHO (72-94 %) and in AP there is also an important contribution (31-42 %).

According to [3], the Spanish energy production profile is almost 60 % dependent of fossil fuels. Therefore, the CO_2 generated from the combustion of coal, oil and natural gas is the main contributor to the GWP and ODP. Besides, consumption of those raw materials is the responsible of the DAR. Acidification of soils is another consequence of the energy production from fossil fuels due to the emission of SO_2 to the atmosphere, wich is oxidated to H_2SO_4 , a water-soluble substance that returns to the surface by means of acid rains, increasing the impact in AP category.

The use of sludge in agriculture as a fertilizer has the main impact in TAETP (98-99 %). This is due to the contents of heavy metals in its composition. Also, this sludge application has a considerable impact in AP (57-66 %), mainly produced by the air emissions of NH_3 gases that are contributors to the acid rains phenomena.

EP impact is mainly attributed to the discharges of the effluent into the receiving waters (85-92 %). Fig. 2 shows the contribution percentage of the effluent main pollutants to this category. As it can be observed, the nitrogen compounds are the main responsible of EP with more than 68 % of the total impact in all strategies whilst COD contribution does not exceed 18 %. In previous LCA studies [3] and [2], phosphorous has been found as

TABLE II: Parameters of the inventory data for the control strategies evaluated. All data are presented per m^3 of influent wastewater

Strategies	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Inputs										
From background system										
Electricity (kWh)	0.2142	0.2246	0.3109	0.3109	0.3109	0.2241	0.2377	0.2241	0.2407	0.2238
Carbon source (kg)	0	0	0	0.0763	0	0	0.06	0	0.0629	0
Outputs										
Emissions to soil										
Sludge for disposal (kg)	0.124	0.124	0.124	0.145	0.122	0.124	0.141	0.123	0.148	0.122
Cd (mg)	1.24	1.24	1.24	1.45	1.22	1.24	1.41	1.23	1.48	1.22
Cr (mg)	0.0124	0.0124	0.0124	0.0145	0.0122	0.0124	0.0141	0.0123	0.0148	0.0122
Cu (mg)	0.0124	0.0124	0.0124	0.0145	0.0122	0.0124	0.0141	0.0123	0.0148	0.0122
Hg (mg)	1.24	1.24	1.24	1.45	1.22	1.24	1.41	1.23	1.48	1.22
Ni (mg)	0.371	0.371	0.371	0.435	0.365	0.371	0.424	0.368	0.443	0.367
Pb (mg)	0.928	0.928	0.927	0.109	0.911	0.927	0.106	0.919	0.111	0.917
Zn (mg)	0.0309	0.0309	0.0309	0.0363	0.0304	0.0309	0.0353	0.0306	0.0369	0.0306
Emissions to water										
Total COD (g)	48.9	49.0	48.9	50.5	49.3	48.9	50.0	49.2	49.1	49.2
Total BOD (g)	2.79	2.79	2.78	3.14	2.80	2.79	3.12	2.81	3.02	2.81
Total N (g)	16.1	15.6	17.8	10.7	18.4	16.5	10.7	15.5	10.9	16.4
Sludge released in water (g)	13.9	13.9	13.9	15.1	14.3	13.9	14.7	14.1	14.1	14.1
Emissions to air										
CH_4 (g)	0.619	0.619	0.618	0.726	0.608	0.618	0.707	0.613	0.739	0.612
N_2O (g)	0.0619	0.0619	0.0618	0.0726	0.0608	0.0618	0.0707	0.0613	0.0739	0.0612
NH_3 (g)	1.21	1.21	1.21	1.42	1.19	1.21	1.39	1.20	1.45	1.20

one of the main substances involved in EP but, in this study this pollutant was not taken into account (is not considered in ASM1) and only the nitrogen, in ammonia and nitrate forms and the chemical oxygen demand (*COD*) contributions are available.

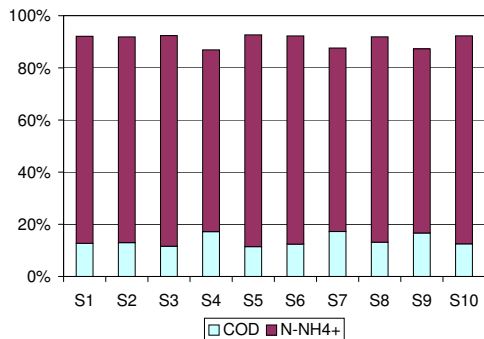


Fig. 2: Relative contribution of $N - NH_4^+$ and *COD* in the effluent to eutrophication

V. COMPARISON BETWEEN CONTROL STRATEGIES

From the set of impact categories mentioned, 4 of them have been selected with different profiles to analyze the behavior of the control strategies implemented. EP is one of the selected impact categories since the main function of wastewater treatment plants is to improve the water quality by removing pollutants. AP, GWP and TAETP categories have been also selected because they are normally used in this kind of processes and because they present different profiles than the rest. PHO, DAR and ODP categories present a profile that can be inferred from GWP impact

results because of as this category, their impacts are mainly dependent from energy consumption.

Attending to the profiles of the control strategies, they can be grouped as:

- 1) **Strategies with carbon source addition (G1):** includes **S4, S7** and **S9**.
- 2) **Strategies without carbon source addition and no aeration energy control (G2):** includes **S3** and **S5**.
- 3) **Strategies without carbon source addition but aeration energy control (G3):** includes **S1, S2, S6, S8** and **S10**.

Referring to fig. 3 results, the following analysis can be done:

For G1, lower impacts are observed in AP (fig. 3a) for combined strategies S7 and S9 (11 % for S7 and 8 % for S9) in relation with S4 impact. The contributions to this category are determined by the energy consumption but also by the heavy metals content in the sludge, aspect where G1 is defavoured compared with G2 and G3 due to its larger sludge production.

Analyzing now the GWP category, it can be noted in fig. 3b an increase in S4 impact respect to the rest of strategies. This increase is due to the consumption of energy in aerobic reactors and the energy needed for the production of the external carbon source added. It should be noted the decreasing impact on this category for the combined strategies of this group (S7 and S9) with respect to S4 (24 % less) and also to G2 (15 % less), given by the fact of aeration control that reduces the energy consumption. Precisely due to this fact of control of aeration and the non use of the external carbon source, G3 has the lowest impact in GWP.

Regarding EP it should be noted that strategies of G1 have the best results (fig. 3c). The fact of using an external

carbon source improves the nitrates removing process, decreasing the quantity of nitrogen compounds present in the effluent and then, decreasing the impact on this category. This can be observed also in fig. 2 where the strategies of G1 have the lowest contribution in nitrates-ammonia ($N - NH_4^+$) but the largest in COD , due to the quantity of organic matter present in the effluent. In G2 and G3, more impact are obtained due to the worse results in the effluent quality but G3 impact is lower than G2 because of the aeration control enhances the nitrification process and then, the effluent quality.

In TAETP category, the impact of G1 is the largest of all groups (fig. 3d). The use of an external carbon source increases the sludge production and consequently its environmental impact since the sludge is used as a fertilizer in agriculture. In the case of G2 and G3, impacts obtained are very similar due to the non use of the external carbon source.

A. Correlations observed

In order to summarize the groups results numerically, table III shows the impact averages of the groups in the selected categories. From this table and taking into account the previous analysis done based on fig. 3, it can be stated that the advantages of G1 respecting to the others are located in the effluent quality due to less impact in EP. But, seen all previous analysis it has been concluded that the impact values obtained in EP by G1 are despite the deterioration of the impact in the rest of categories. Many factors can influence these results but as has been said before, if a good effluent quality is desired, this quality should be paid and, as it has been demonstrated in this work, not only from the economical point, but also from the environmental.

TABLE III: Average impact of groups in selected categories

Impact category	G1 (S4, S7, S9)	G2 (S3, S5)	G3 (S1, S2, S6, S8, S10)
AP (kg SO_2 eq.)	$4.03 \cdot 10^{-3}$	$3.76 \cdot 10^{-3}$	$3.29 \cdot 10^{-3}$
GWP (kg CO_2 eq.)	$1.69 \cdot 10^{-1}$	$1.79 \cdot 10^{-1}$	$1.26 \cdot 10^{-1}$
EP (kg PO_4^{-3} eq.)	$6.45 \cdot 10^{-3}$	$9.39 \cdot 10^{-3}$	$8.48 \cdot 10^{-3}$
TAETP (kg 1,4-DCB eq.)	$3.19 \cdot 10^{-3}$	$2.71 \cdot 10^{-3}$	$2.71 \cdot 10^{-3}$

By other hand, G2, as a group, has the worst results in GWP and EP due to its larger energy consumption since no control is applied in aerobic reactors and the high $N - NH_4^+$ concentration in the effluent derived of an incomplete nitrification process. The generation of sludge on this group, that is comparable with G3, does that TAEPT impact be 15 % lower than G1. The balance between GWP and TAETP impacts makes possible that the AP impact of this group can be comparable with S7 and S9 (fig. 3a), as was said before, but is still approximately a 12 % larger than G3 impact.

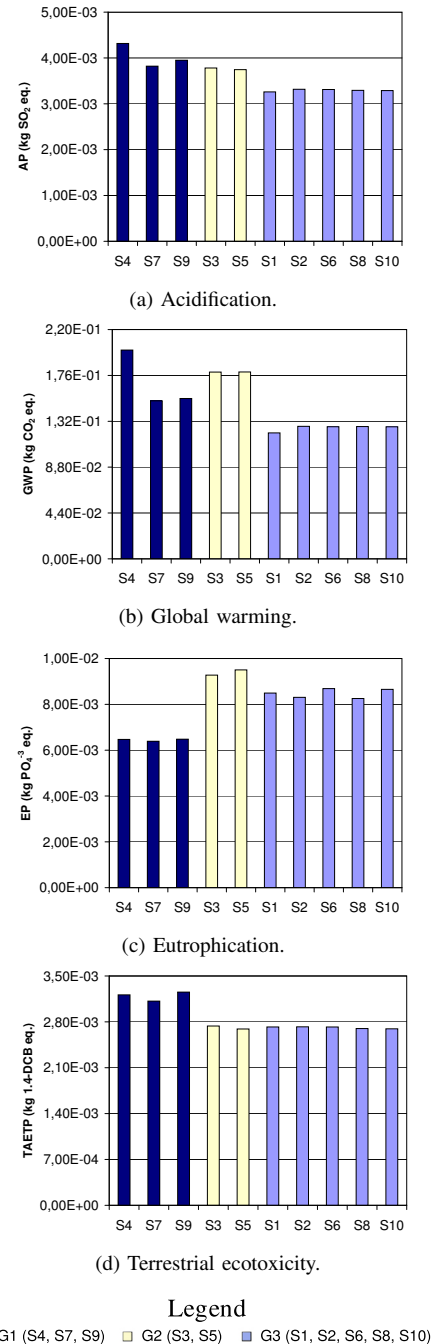


Fig. 3: Total impact of strategies (by groups) in selected categories

G3 has the best group results in GWP and AP due to the aeration control applied, which reduces the energy consumption and thus, the respective impacts. In TAETP, the impact associated is as for G2 (fig. 3d) due to the fact that no external carbon is added and therefore, the sludge amount produced and its corresponding heavy metals concentration are lower than G1. Although in S6 and S10 a strategy to control nitrates (S3) is used, the

impact of these combined strategies in EP highlights that the nitrates removal efficiency is more enhanced when the external carbon source (Q_{carb}) is manipulated than when the internal recycle flow rate (Q_a) is manipulated.

VI. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

The main correlations found between the groups of strategies and the impact categories are:

- **Strategies with carbon source addition (G1):** The use of an external carbon source allows to reduce the nitrates concentration and therefore, to achieve the lowest EP impact. However, it produces an increase in the sludge, affecting TAETP and AP categories. Also, the energy and resources needed to produce the chemical compound added produces a larger impact in the rest of the categories. This means that the lowest impact in EP achieved is despite increasing impact in the rest of categories.
- **Strategies without carbon source addition and no aeration energy control (G2):** These strategies have a large impact in all categories, except in TAETP, because no control of aeration and no external carbon source is added. Therefore, this group is the less recommendable for implementing by they own.
- **Strategies without carbon source addition but aeration energy control (G3):** This group presents the lowest impact associated to TAETP and GWP categories but its impact in EP category is high. Due to GWP category has the same profile than the rest of energy dependent categories (PHO, DAR, ODP, AP), it can be inferred that this group has the lowest impact on previously mentioned categories.

B. Future Works

Once identified the main contributors for each impact category, research will focus on how to decrease those impacts by optimizing the control applied in each part of the plant. This could be done by means of new control techniques that improve the plant performance but always taking into account the economical costs associated to possible modifications.

VII. ACKNOWLEDGMENTS

This work has received financial support from the Spanish CICYT program under grant DPI2010-15230. Dr Ulf Jeppsson, from the Electrical Engineering Faculty of Lund University, Sweden, is gratefully acknowledged for providing the BSM1 Matlab/Simulink code.

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