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SUMMARY OF DOCTORAL DISSERTATION

THE OPTIMIZATION OF CONTROL IN INDUSTRIAL FACILITIES CONSIDERING MINIMIZATION OF ENERGY CONSUMPTION

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AKADEMIA GÓRNICZO-HUTNICZA IM. STANISŁAWA STASZICA W KRAKOWIE

DZIEDZINA NAUK INŻYNIERYJNO-TECHNICZNYCH

DYSCYPLINA AUTOMATYKA, ELEKTRONIKA I ELEKTROTECHNIKA

AUTOREFERAT ROZPRAWY DOKTORSKIEJ

OPTYMALIZACJA STEROWANIA OBIEKTAMI PRZEMYSŁOWYMI Z UWZGLĘDNIENIEM KRYTERIUM MINIMALIZACJI ZUŻYCIA ENERGII

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Introduction

Currently, the energy industry is undergoing a breakthrough transformation, which is manifested through the dispersion of energy sources. This transformation is associated with the challenge of making the energy system more flexible in terms of its operation. The need for transformation is caused by the climate changes observed in recent years, which entail the need to reduce CO_2 emissions. The result is an increase in electricity prices, which encourages the industry to minimize energy consumption. The author's interests focus especially on the issues of power installations in industrial applications. Doctoral dissertation entitled OPTIMIZATION OF CONTROL OF INDUSTRIAL FACILITIES, TAKING INTO ACCOUNT THE CRITERION OF MINIMIZATION OF ENERGY CONSUMPTION concerns these practical problems. The work is based on data from the existing wastewater treatment plant at the Płaszów Sewage Treatment Plant in Krakow. The sewage treatment plant is a modern facility that meets most of the latest environmental and energy standards. This treatment plant is an example of an installation serving a large area of the Krakow agglomeration. It is worth emphasizing the importance of this facility due to the fact that it is a significant consumer of electricity.

Aim and scope of the thesis

In such a complex facility as a wastewater treatment plant, energy consumption is influenced by many factors that must be thoroughly analyzed. It is necessary to study the entire wastewater treatment process in detail to determine which step has the greatest impact on energy consumption. Modeling of wastewater treatment plants to reduce energy consumption is the main topic of this work. The author assumes that control optimization can be numerically implemented in digital twin, i.e. the virtual model of such an industrial facility .

Thesis

The author has put forward the thesis that "*Comprehensive modeling of the industrial facilities like wastewater treatment plants can be used in optimization of control leading to minimization of electric energy consumption*".

Selected research methods and research results

The change in the inflowing sewage affects the treatment process. More precisely, depending on the quality of wastewater, the expected oxygen level in the reactors changes. The oxygen content in the reactors, on the other hand, is controlled by the air pumped into the reactors. The blowers regulate the pressure to maintain the expected air flow. Their operation consumes a significant amount of electricity. Hence, aeration process is analyzed, as it is the most energy-intensive part of the process. This paper discusses the available modifications to the control of the municipal sewage treatment plant and real measurement data was used to build the model, validate it and simulate it in terms of reducing electricity consumption.

To enable energy optimization of the treatment plant facility, a Matlab/Simulink digital twin of installation was prepared. Complex numerical model such as Activated Sludge Model 1 (ASM1) was used to model reactor in wastewater treatment. The author of dissertation discussed various solutions based on ASM1 and decided to use the Benchmark Simulation Model 1 (BSM1) environment to simulate the reactor (example result is presented in Fig. 1).

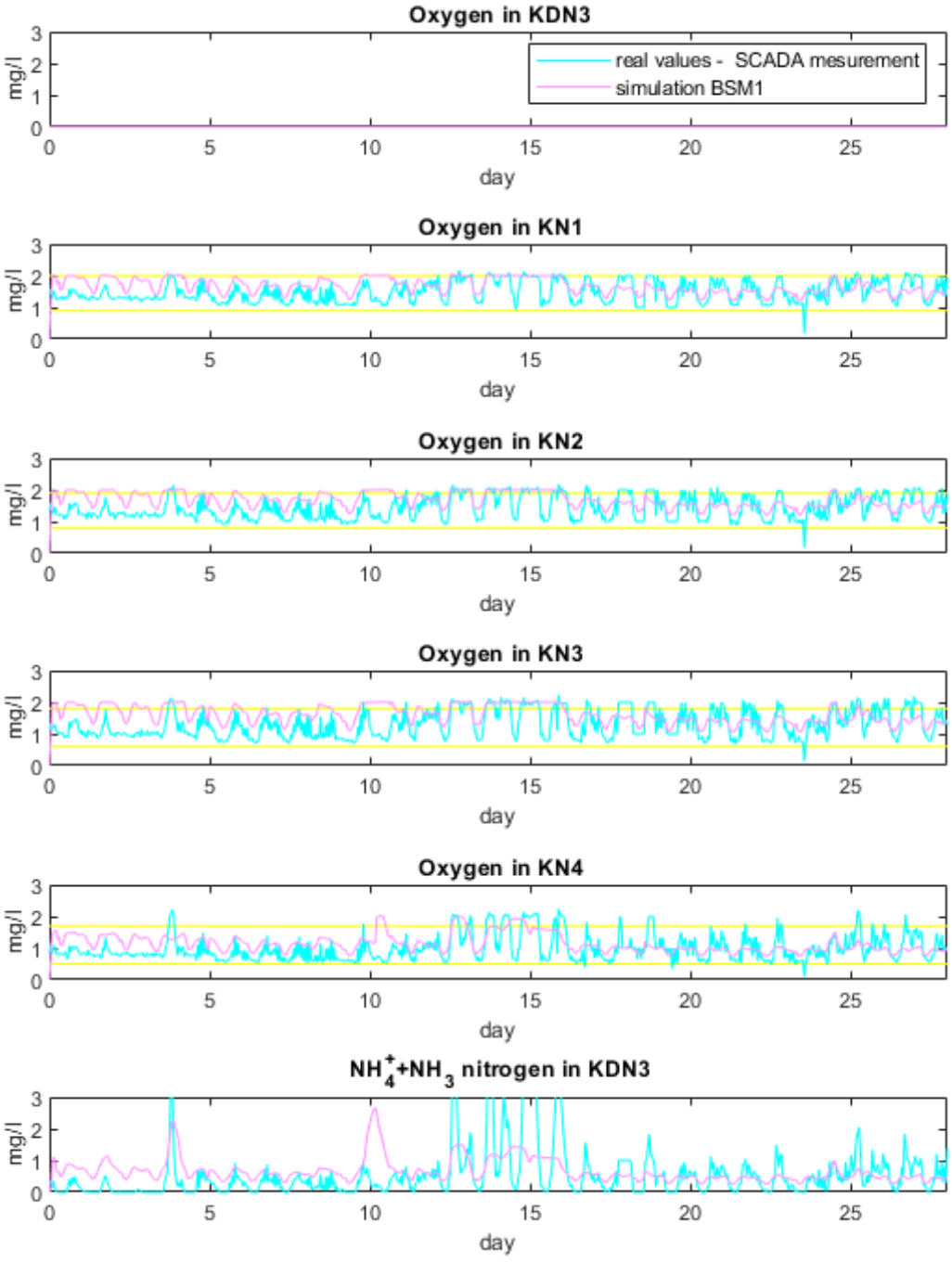

Fig. 1. Simulation of reactor using CONSTAINFLUENT signal as input to WWTP

Next, detailed analysis of the model and measurement data allowed to build a model of blowers. Measurements from a real object were used to model the characteristics of individual blowers. Thanks to this numerical model, various control strategies can be freely tested without interfering with the operation of the existing installation (Fig. 2)

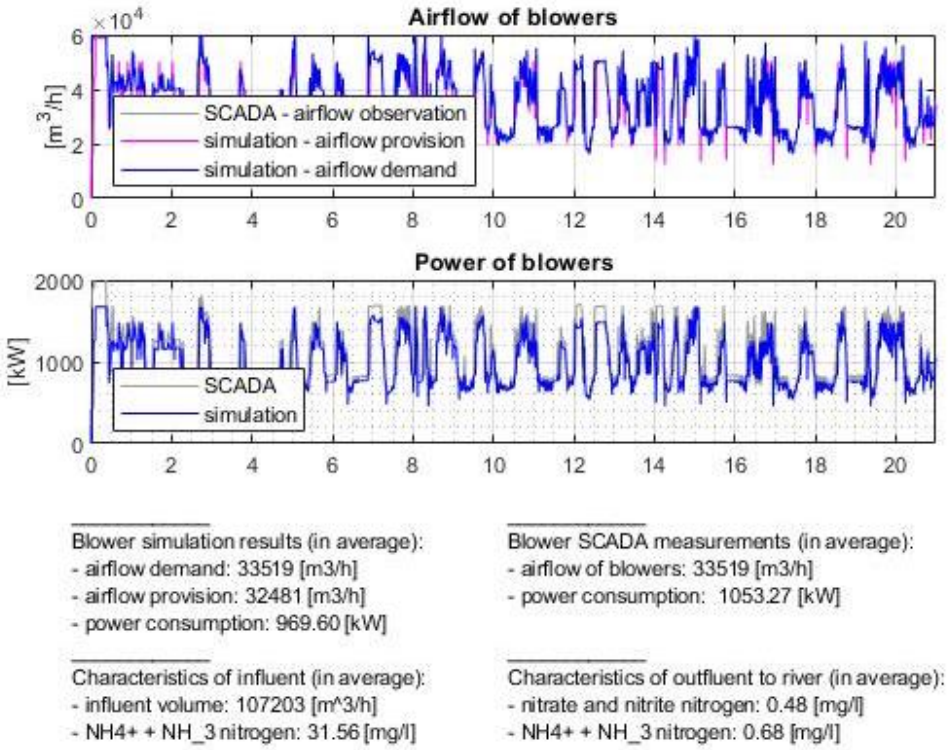

Fig. 2. Total airflow and power consumption – Results of simulation for T_{OFF_DELAY} equals 1h, T_{ON_DELAY} equals 1h with SCADA

The target implementation merged the models of reactor and blowers and then validated the model with measurements (Fig. 3). This numerical model of the sewage treatment plant reactor was used to control oxygenation in order to reduce electricity consumption. The simulation environment greatly simplifies the conduction of experiments.

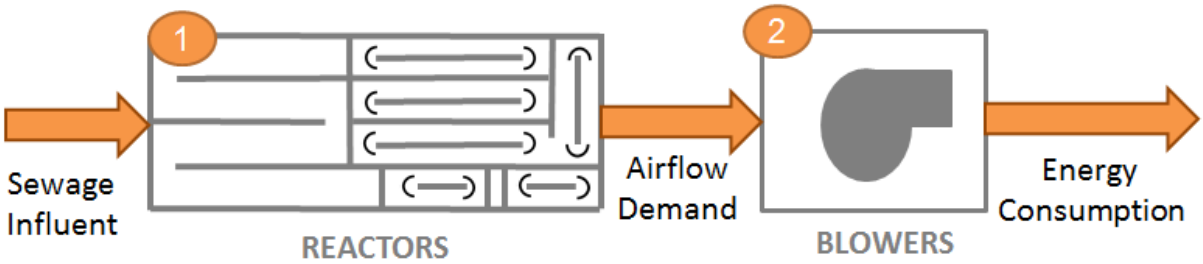

Fig. 3. General scheme of the purification process presented in the dissertation

Validation of the model operation was carried out, which consists in examining the parameters implemented in the model. Selected model validation techniques were investigated as tools for testing the model of reactors process characteristics. Initially, the Morris analysis revealed the parameters most relevant to the wastewater treatment process and sewage influent. Fig. 4 presents particular importance of SNH (NH_4^++NH_3 nitrogen) and Q (flow rate).

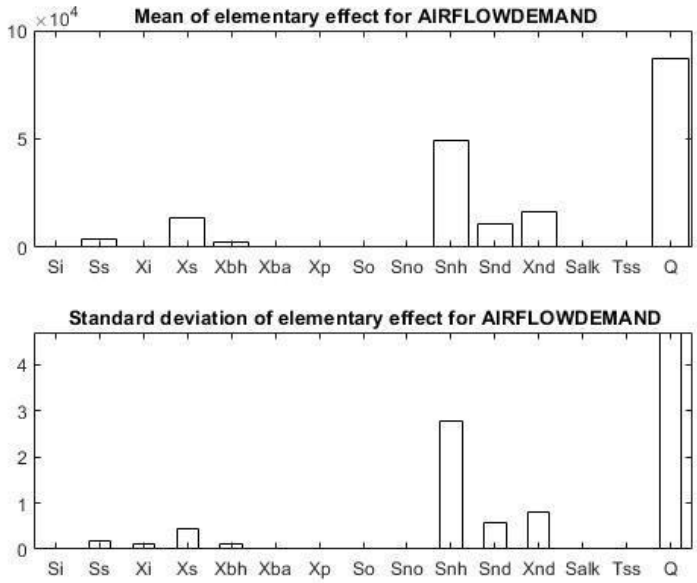

Fig. 4. The standard deviation airflow demand in Morris simulation depending on the quality of the influent

The author implemented state estimation to check the wastewater treatment process and identify the unknown parameters using the Extended Kalman Filter (Fig. 5).

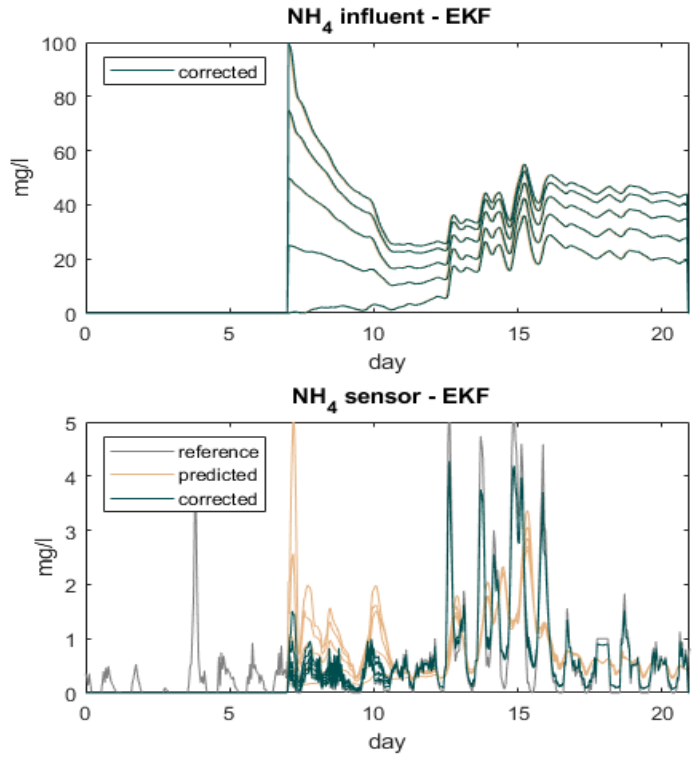

Fig. 5. Simulation results for EKF with initial conditions between 0 – 100

The conducted field inspection and literature review indicate the potential of modifying the blower control algorithm to reduce the energy used by the blowers during the aeration process. The main purpose of the work is to analyze optimal control strategies of wastewater treatment plants using numerical models of these facilities. This avoids the necessary experiments on the real object.

The author focused on the preparation of a test procedure to control reactors and blowers exploiting numerical model. Based on the observations and literature review, the author decided to change the switching time and downtime of the blowers in order to select the optimal operation of the station of six blowers in the installation. Fig. 6 presents the scheme of simulations in the analysis and results are presented in Tab. 1.

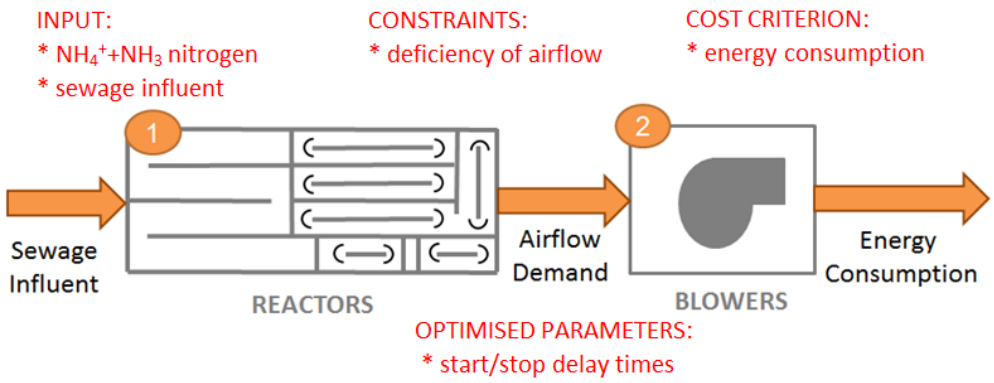

Fig. 6. Scheme of simulations in the analysis

Tab. 1. Abstract of simulation results in the analysis

SIM NR.	BLOWERS' DELAY		SUPPLIED AIRFLOW				ENERGY CONSUMPTION	
	T_{ON_DELAY}	T_{OFF_DELAY}	Reactor demand	Provision by blowers	Mean Deficiency	Mean Deficiency	Mean Energy	Change of Energy
	[h]	[h]	[m^3/h]	[m^3/h]	[m^3/h]	[%]	[kW]	[%]
1-9	1	1	33668,74	33548,48	120,26	0,46	1010,72	100
10-18		2	33668,74	33537,50	131,24	0,54	1013,27	100,25
19-27		4	33668,74	33548,56	120,18	0,53	1018,22	100,74
28-36	2	1	33668,74	33417,46	251,29	0,83	1004,67	99,40
37-45		2	33668,74	33391,18	277,56	0,91	1007,08	99,64
46-54		4	33668,74	33488,78	179,96	0,70	1015,19	100,44
55-63	**4**	**1**	**33668,74**	**33090,53**	**578,22**	**1,70**	**990,99**	**98,05**
64-72		2	33668,74	33118,56	550,19	1,66	994,84	98,43
73-81		4	33668,74	33244,82	432,92	1,34	1004,47	99,38

Turning to the analysis of the presented results, it can be concluded that evidently the case of operation with $T_{ON\_DELAY}=4h$ and $T_{ON\_DELAY}=1h$ gives lower energy consumption for operation for different influent quality. Extending the T_{ON_DELAY} value from 1 hour to 4 hours can reduce the electricity consumption by 1,95%. The simulation of the treatment plant as a whole has shown the possibility of reducing the consumption to 98.05% of the initial value.

On the other hand, delaying the activation of the blowers leads to short situations in which the amount of oxygen deviates from the demand. In presented above simulation the airflow deficiency reaches 1,70%. Hypoxia in the rectors must be taken into consideration. Oxygen deficiencies can be made up by increasing the efficiency of blower after it is switched on because the amount of oxygen in the reactor can slightly fluctuate.

Summary

Summarizing, the control strategy presented in dissertation is based on digital twin of existing installation. Complex numerical model such as Activated Sludge Model 1 (ASM1) was used to model reactor in wastewater treatment using Benchmark Simulation Model 1 (BSM1).

The Morris screening and the use of identification procedures emphasize the rationality of the conducted research. The author describes some specific conclusions that the influent quality, especially NH_4^++NH_3 nitrogen, and its volume lead to the observation of the impact of to the consumption of electricity.

Optimization of control by modifying the blower operation allows to reduce electricity consumption in the sewage treatment plant. Theoretically, better operation points can be achieved by blocking the blowers leading to switching in better performance. Thanks to its use, it was possible to achieve the goal of the dissertation - to prove the possibility of using energy optimization algorithms in industrial sewage treatment plant installations. On the other hand, delaying the activation of the blowers leads to short situations in which the amount of oxygen deviates from the demand.

With the above results the author confirms the assumption of thesis that *comprehensive modeling of the industrial facilities like wastewater treatment plants can be used in optimization of control leading to minimization of electric energy consumption.*

The author declares the following issues are characterized by originality:

- The implementation discussed in the dissertation is an in-depth case study of an existing sewage treatment plant in Kraków Płaszów. The presented work is a complete realization that integrates various issues in this WWTP. The previously described literature examples deal with other objects and do not cover operation of this wastewater treatment as a whole;
- The author presents a novel method of controlling the blowers by changing the time that on/off blowers turn on and off. This control algorithm allows some savings of several percent in electricity consumption.

Based on the presented digital twin, the research can go beyond the standard scenarios available in a real wastewater treatment plant. Therefore, the conducted experiment consisting in controlling the time of switching on and off the blowers does not exhaust the possibilities. In the future, parameters can be tested not only in terms of reducing electricity consumption, but also issues related to the quality of the treatment process, it is possible to experiment with unreal parameters of sewage, etc. Further research may be done in the future.

Context

The analysis presented in the paper is an in-depth case study of an existing sewage treatment plant. The work includes the implementation of a complex simulation of biological sewage reactors in the Płaszów Sewage Treatment Plant. This analysis is probably the first such approach for the Krakow sewage treatment plant. It is worth noting that initially the research was carried out in cooperation with Wodociągi Krakowskie (formerly MPWiK) as part of a joint project. The subject of the work results from the author's research carried out as part of this project. Thanks to this project, the author obtained the necessary measurements needed to model this treatment plant.

However, it should be noted that the industry of industrial wastewater treatment plants is vast. The case presented in the dissertation is a detailed implementation of a specific treatment plant - the facility of the Płaszów Sewage Treatment Plant. The numerical model implemented as part of this work is only the first stage. The author's knowledge and completed projects allow the use of resources to further optimize the operation of this treatment plant and implement a similar algorithm in other treatment plants. It is easy to imagine other treatment plants whose modeling can be the basis for the implementation of optimization algorithms. Each such facility has its own specific specification that requires detailed analysis.

All the issues cited are supported by a literature review. Preparing the dissertation for many years, the author collected numerous literature sources, the most important of which were quoted in the work, and references to them can be found in the bibliography. Selected issues of the model and optimization results were published in scientific articles, which were mentioned in the dissertation.

List of major publications

[1] P. Król, A. Gallina, and G. Bazior, “Metody zarządzania handlem energią elektryczną na rynku międzynarodowym,” in *Aktualne zagadnienia z zakresu energetyki*, 2018.

[2] P. Król and G. Krajačić, “Energy Analysis of Municipal Waste in Dubrovnik,” *Acta Innovations*, 2018.

[3] P. Król, K. Nowakowski, and G. Bazior, “Zastosowanie technologii Hyperledger w zadaniu optymalizacji energetycznej,” in *Projektowanie mechatroniczne : zagadnienia wybrane : praca zbiorowa*, 2018.

[4] P. Król, A. Gallina, M. Lubieniecki, T. Uhl, and T. Żaba, “Sensitivity analysis of a municipal wastewater treatment plant model,” *MATEC Web Conf.*, vol. 252, 2019.

[5] P. Król, M. Lukawski, J. W. Tester, M. C. Moore, and C. L. Anderson, “Demand Response for Reducing Coincident Peak Loads in Data Centers,” *Proc. 52nd Hawaii Int. Conf. Syst. Sci.*, no. January, 2019.

[6] P. Król, W. Klimasz, A. Gallina, and P. Zagórski, “Characterization of an Helmholtz cage used for satellite ADCS testing,” in *Wybrane zagadnienia dynamiki układów mechatronicznych : praca zbiorowa*, 2020.

[7] P. Król, P. Zagórski, and A. Gallina, “Batch Algorithm for Balancing the Air Bearing Platform,” in *Advanced, contemporary control : proceedings of KKA 2020*, 2020.

[8] P. Król, A. Gallina, and T. Uhl, “Sewage influent estimation in BSM1 model of Płaszów WWTP,” *IDAACS’2021*, 2021.