JEE Journal of Ecological Engineering
Volume 20, Issue 9, October 2019, pages 103–115
https://doi.org/10.12911/22998993/112501

Received: 2019.08.07
Revised: 2019.08.20
Accepted: 2019.09.19
Available online: 2019.09.30

Methodology for Energy Efficiency and Sustainability Improvement of Batch Production Systems on the Example of Autothermal Thermophilic Aerobic Digestion Systems

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ABSTRACT
The present study proposes a methodology for energy efficiency and sustainability improvement of the operating conditions of batch production systems. The methodology involves applying a conventional system for municipal wastewater treatment using the process of Autothermal Thermophilic Aerobic Digestion (ATAD) of sludge. Its sustainable operation is essential for the quality of the treated sludge and the reduction of environmental impact. An analysis of the possibilities for energy integration of processes in ATAD systems was performed. The structures for indirect energy integration of processes using storage tanks and mathematical models for describing energy integration for the studied object were proposed. The models are included within a two-stage stochastic optimization problem together with constraints on the physical, technical and technological feasibility of the integration frameworks and temperature constraints with an optimization criterion minimum redesign cost. The obtained results show significant energy savings as a result of energy integration and sustainability to temperature conditions in bioreactors.

Keywords: sustainability, energy integration, batch production system, mathematical modeling, stochastic optimization, ATAD process.

INTRODUCTION

Sustainable development is a way of using natural resources that aims at meeting human needs while maintaining the natural balance with the environment so that these needs can be met both in the present moment and for future generations. The integration of energy and mass processes is one of the most powerful tools for creating sustainable and energy efficient production systems, [6]. Circular integration combines the elements from process integration, industrial ecology, and circular economy to provide an engineering tool box for planning a sustainable and circular economy [17].

Over the last decades, the focus for energy integration of processes has shifted from the integration of the processes in continuous production systems to the batch production systems. In the latter, the problem is much more complicated due to the presence of low grade heat and the discrete nature of the sources and sinks of heat. The energy consumption of wastewater treatment plants at two food processing plants was evaluated by analyzing different system loads and how they affect the energy consumption [18]. Mobilization and utilization of internal energy resources of production systems to overcome the impact of many external uncertaintes fits into the concept of energy efficiency and sustainability. Mathematical modeling methods are used to overcome the impact of these uncertain parameters and new algorithms are required [11], in addition to efficient computational tools for solving multi-parameter mixed integer linear and nonlinear stochastic optimization problems [8, 9, 15]. This is a new challenge related to finding the conditions for the sustainability of production systems with batch processes, in the creation of methods and approaches for their energy integration in continuous and batch production systems [1, 13, 14], as well as in the creation of new effective computational tools to handle complex optimization problems [11, 15]. The studies show that the production systems with batch processes have sufficient energy potential which can be used to improve their energy efficiency. The recovery and reuse of this heat is hampered by the batch mode of operation of the production systems. It is further complicated by the effects of stochastic flow parameters such as temperature, volume, etc., overcoming which remains an open and still unsolved problem.

This requires the creation of a common methodology using a systematic approach combining the most appropriate methods for the analysis, synthesis and optimization of production systems with batch processes, to improve their energy efficiency and sustainability, which is the main problem addressed in this work.

METHODOLOGY FOR CREATING THE ENERGY EFFICIENT AND SUSTAINABLE PRODUCTION SYSTEMS

The proposed methodology combines the following methods and techniques:

- Energy analysis of the production systems with batch processes;
- Synthesis of the structures for energy integration of batch production systems;
- Modeling of the energy-integrated batch production systems;
- Models incorporating within a two-stage stochastic optimization problem;
- Analysis and verification of the solutions obtained.

It is applied for energy efficiency and sustainability improvement of the operating conditions of a conventional system for municipal wastewater treatment using the process of Autothermal Thermophilic Aerobic Digestion (ATAD) of sludge.

WASTEWATER TREATMENT SYSTEM USING AUTOTHERMAL THERMOPHILIC AEROBIC DIGESTION OF SLUDGE

An industrial conventional ATAD system for municipal wastewater treatment was used as an example to demonstrate the methodology efficiency. The process was carried out in parallel series of sequentially connected bioreactors, where the wastewater is treated at different operating temperatures with the help of thermophilic aerobic microorganisms having exothermic metabolism. The heat released into the system contributes to conducting stabilization of the treated in the first bioreactors stage sludge at temperatures of about 55°C and killing of pathogens in the second bioreactors stage at a desired temperature of 65°C [12]. The system under consideration consists of four identical bioreactors with a working volume of 100 m^3. The reactors are organized in two independent series of two bioreactors (Figure 1). Usually, only one series operates during the winter season, while both operate during the summer season.

The feeding with raw sludge is semi-batch process and independent for each series. As a

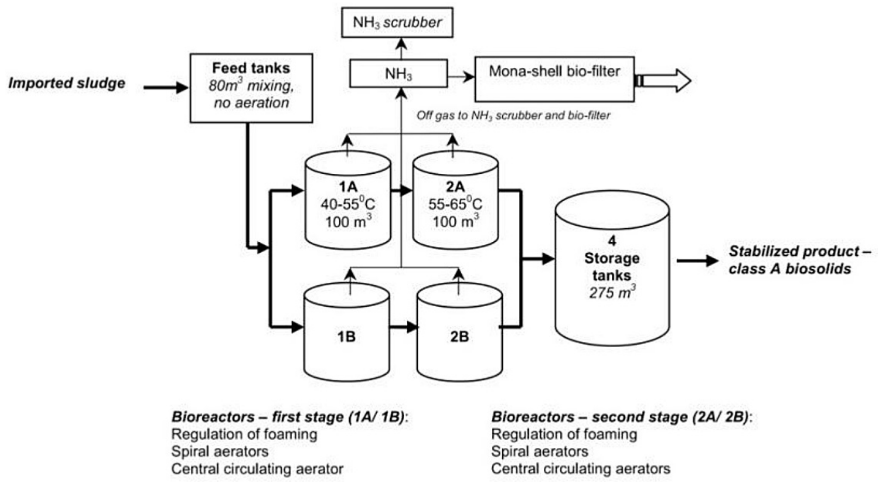


Figure 1. Two-stage conventional ATAD system [7]

result, the operating temperatures in bioreactors decrease causing a thermal shock to the thermophilic microorganisms. Hence, the operating temperatures in the first bioreactor stages and the temperature in the entire system are reduced. It hampers the biodegradation process. The hydraulic rentention time is prolonged and the energy costs for mixing and aeration increase.

ENERGY ANALYSIS OF BATCH PRODUCTION SYSTEMS

A statistical analysis of one-year records of flows data of an industrial ATAD shows that the energy efficiency of the process depends on: the volume, the temperature and composition of incoming raw sludge, the temperature of partially treated sludge, the ambient temperature, etc. These parameters are stochastic (uncertain) and have a significant impact on the sustainable operation of the entire ATAD system. The problem with uncertain temperatures can be overcome by limiting the impact of the stochastic input parameters. Layden and co-authors, supposed that the use of available low grade heat in the system and its recovery can reduce the temperature fluctuations in the first bioreactor stages and provide sustainable operating temperatures for ATAD facilities [7]. However, this process is hampered by discrete character of the batch system. Often, the flows suitable for energy integration have shifted and occur at different time intervals.

From the data provided for the considered ATAD system, it was found that about 2681.4 and 3350.52 [MJ] of waste heat were released into the environment with the outgoing from the second bioreactors stage hot "end-product".

However, the utilization of this heat is hampered by the following factors:

- Charging and discharging operations of bioreactors are discrete and shifted in the time. The flow candidates of energy integration appear in batch mode and at different time intervals.
- The integration process is further complicated by the presence of stochastic fluctuations in the values of the flow parameters that are candidates for energy integration.

Therefore, in order to overcome the effects of stochastic factors and to provide the efficient use of waste heat for the sustainable operation of ATAD facilities, the issue of design/redesign of the production system for the energy integration of batch flows under uncertainties needs to be addressed as a problem of stochastic optimization. Designing a heat exchangers scheme is an extremely difficult task, due not only to its nonlinear characteristics but also to the presence of a large number of local optimums in solving the formulated optimization problems.

SYNTHESIS OF STRUCTURES FOR ENERGY INTEGRATION OF ATAD SYSTEMS

The present study applies the concept of [2–4] for heat integration into a system of bioreactors, operating at different time intervals using one common and two different heat storage tanks. It is implemented and adapted for the considered ATAD system and it is illustrated in Figure 2. The superstructure is obtained through the concepts for storing "heat" and "cold" in batch production systems using one or two heat storage tanks – *HS*.

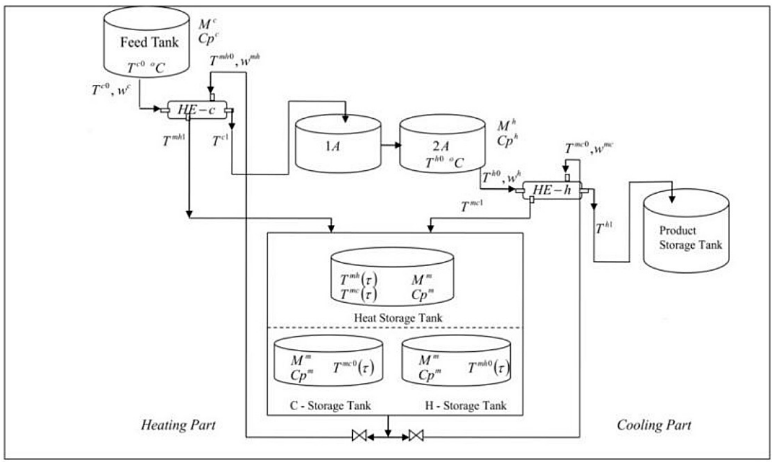


Figure 2. General framework for the heat integration of flows in the ATAD system

The heat transfer is carried out by means of two heat exchangers – *HE-c*, for heating the cold raw sludge coming into ATAD system and *HE-h* for cooling the hot "end-product" outgoing from the second bioreactor to the product tank. The transport of the respective flows through heat exchangers is carried out by means of pumps.

Conditionally, the integrated ATAD system is divided into the heating and cooling parts. The fluid stored in the structure of the heat storage tanks – *HS* is used as heating or cooling intermediate agent at different time intervals. Starting from the heating part, the scheme works as follows: The fluid stored as "hot", with an initial temperature T^{mh0} passes through the heat exchanger *HE-c* for a time period of τ^c transferring heat to the cold sludge, cools and returns to *HS*. At the end of the heating process, the intermediate fluid is cooled to temperature T^{mc0}, which is initial for the process of cooling the hot fluid outgoing from the bioreactor 2A. It passes through heat exchanger – *HE-h* for a time period of τ^h, cools the hot fluid and returns heated to the heat storage tanks. At the end of the cooling process the temperature in *HS* is T^{mh0}. The heating and cooling processeses in the heat exchangers, as well as those in the heat storage tank are non-stationary. The heat exchangers operate in the counter-current mode.

Depending on the configuration selected from the heat storage tanks, through mathematical descriptions, in the case of one common hot/cold heat storage tank and in the presence of two separate hot and cold heat storage tanks, the temperatures at the end of the heating and cooling processes at the outlets of the heat exchangers, as well as the initial temperatures T^{mh0} and T^{mc0} in heat storage tanks, are determined.

MODELING OF ENERGY-INTEGRATED PRODUCTION SYSTEMS WITH BATCH PROCESSES

For this purpose the approach of [16] is applied as follows:

<table>
<tr><th>One heat storage tank – model M1</th><th>Two heat storage tanks – model M2</th></tr>
<tr><td colspan="2"><u>Heating part</u> - temperatures at inlets and outlets of the heat exchanger HE-c</td></tr>
<tr><td colspan="2">Cold fluid enters the heat exchanger HE-c with temperature T^{c0}, which is known and comes out with temperature T^{c1}</td></tr>
<tr><td>$T^{c1}(\tau^c) = T^{c0} + [T^{mh}(\tau^c) - T^{c0}]R^c\Phi e^c$,
$R^c = \frac{w^{mh}cp^m}{w^c cp^c}$; $w^c = \frac{M^c}{\tau^c}$ [kg/s];
$w^{mh} = \frac{M^m}{\tau^c}$ [kg/s],
$\Phi e^c = \frac{1-\exp(-y^c U^c A^c)}{1-R^c\exp\left(-y^c U^c A^c\right)}$;
$y^c = \frac{1}{w^{mh}cp^m} - \frac{1}{w^c cp^c}$.</td><td>$T^{c1} = T^{c0} + \left(T^{mh0} - T^{c0}\right)R^c\Phi e^c$.
$R^c = \frac{w^{mh}cp^m}{w^c cp^c}$; $w^c = \frac{M^c}{\tau^c}$ [kg/s];
$w^{mh} = \frac{M^m}{\tau^c}$ [kg/s]
$\Phi e^c = \frac{1-\exp(-y^c U^c A^c)}{1-R^c\exp\left(-y^c U^c A^c\right)}$;
$y^c = \frac{1}{w^{mh}cp^m} - \frac{1}{w^c cp^c}$</td></tr>
<tr><td colspan="2">Temperatures of hot intermediate fluid at inlet T^{mh} and at outlet T^{mh1} of HE-c, at the end of the heat exchange process τ^c are as follows:</td></tr>
<tr><td>$T^{mh}(\tau^c) = T^{c0} + \left(T^{mh0} - T^{c0}\right)\exp(-G^{mh}\Phi e^c \tau^c)$.
$G^{mh} = \frac{w^{mh}}{M^m}$ [s⁻¹];</td><td>$T^{mh} = T^{mh0}$</td></tr>
<tr><td>$T^{mh1}(\tau^c) = T^{mh}(\tau^c) - \left[T^{mh}(\tau^c) - T^{c0}\right]\Phi e^c$,</td><td>$T^{mh1} = T^{mh0} - \left(T^{mh0} - T^{c0}\right)\Phi e^c$</td></tr>
</table>

<table>
<tr><th>One heat storage tank – model M1</th><th>Two heat storage tanks – model M2</th></tr>
<tr><td colspan="2"><u>Cooling part</u> - temperatures at inlets and outlets of a heat exchanger HE-h</td></tr>
<tr><td colspan="2">Hot fluid enters the heat exchanger HE-h with temperature T^{h0}, which is known and comes out with temperature T^{h1}</td></tr>
<tr><td>

$$T^{h1}(\tau^h) = T^{h0} - \left(T^{h0} - T^{mc}(\tau^h)\right)\Phi e^h$$

$$R^h = \frac{w^h cp^h}{w^{mc} cp^m}; \quad w^h = \frac{M^h}{\tau^h} \ \text{[kg/s]};$$

$$w^{mc} = \frac{M^m}{\tau^h} \ \text{[kg/s]};$$

$$\Phi e^h = \frac{1 - \exp\left(-y^h U^h A^h\right)}{1 - R^h \exp\left(-y^h U^h A^h\right)};$$

$$y_h = \frac{1}{w^h cp^h} - \frac{1}{w^{mc} cp^m};$$

</td><td>

$$T^{h1} = T^{h0} - \left(T^{h0} - T^{mc0}\right)\Phi e^h$$

$$R^h = \frac{w^h cp^h}{w^{mc} cp^m}; \quad w^h = \frac{M^h}{\tau^h} \ \text{[kg/s]};$$

$$w^{mc} = \frac{M^m}{\tau^h} \ \text{[kg/s]};$$

$$\Phi e^h = \frac{1 - \exp\left(-y^h U^h A^h\right)}{1 - R^h \exp\left(-y^h U^h A^h\right)};$$

$$y_h = \frac{1}{w^h cp^h} - \frac{1}{w^{mc} cp^m};$$

</td></tr>
<tr><td colspan="2">Temperatures of the intermediate fluid at inlet of heat exchanger at the moment τ^h is T^{mc} and at outlet is T^{mc1}</td></tr>
<tr><td>

$$T^{mc}(\tau^h) = T^{h0} + \left(T^{mc0} - T^{h0}\right)\exp\left(-R^h \Phi e^h G^{mc} \tau^h\right)$$

$$G^{mc} = \frac{w^{mc}}{M^m}$$

</td><td>

$$T^{mc} = T^{mc0}$$

</td></tr>
<tr><td>

$$T^{mc1}(\tau^h) = T^{mc}(\tau^h) + \left(T^{h0} - T^{mc}(\tau^h)\right) R^h \Phi e^h$$

</td><td>

$$T^{mc1} = T^{mc0} + \left(T^{h0} - T^{mc0}\right) R^h \Phi e^h$$

</td></tr>
<tr><td colspan="2">Heat storage tanks</td></tr>
<tr><td colspan="2">T^{mh0} and T^{mc0} are the initial “hot” temperature of the intermediate fluid in the heat storage tank obtained at the end of the cooling process of the hot part of the system and the initial "cold" temperature of the intermediate fluid obtained at the end of the heating process of the cold part of the system.</td></tr>
<tr><td>

$$T^{mh0} = \frac{b^{22} + b^{12} b^{21}}{1 - b^{11} b^{21}}$$

$$T^{mc0} = \frac{b^{12} - b^{11} b^{22}}{1 - b^{11} b^{21}}$$

$$b^{11} = \exp(-G^{mh} \Phi e^c \tau^c);$$

$$b^{12} = \left[1 - \exp\left(-G^{mh} \Phi e^c \tau^c\right)\right] T^{c0}$$

$$b^{21} = \exp(-R^h \Phi e^h G^{mc} \tau^h);$$

$$b^{22} = \left[1 - \exp\left(-R^h \Phi e^h G^{mc} \tau^h\right)\right] T^{h0}$$

</td><td>

$$T^{mh0} = \frac{\Phi e^c \left(R^h \Phi e^h - 1\right) T^{c0} - R^h \Phi e^h T^{h0}}{\left(R^h \Phi e^h - 1\right)\left(\Phi e^c - 1\right) - 1}$$

$$T^{mc0} = \frac{\left(\Phi e^c - 1\right) R^h \Phi e^h T^{h0} - \Phi e^c T^{c0}}{\left(R^h \Phi e^h - 1\right)\left(\Phi e^c - 1\right) - 1}$$

</td></tr>
</table>

- firstly, the mathematical descriptions of the heat exchange in the heating and cooling part of the proposed scheme are created separately;
- then the two descriptions are combined into one by solving the models of the heat storage tanks.

The following data must be given:
- M^m – the mass of fluid in the heat storage tank [kg];
- cp^m– the specific heat capacity of the fluid in the heat storage tank [J/(kg.^{0}C)];
- M^c– the mass of the fluid to be heated [kg];
- cp^c– the specific heat capacity of the fluid to be heated [J/(kg. ^{0}C)];
- T^{c0}– the temperature of the cold sludge to be heated [^{o}C];
- A^c– the heat exchange surface of *HE-c* [m^2];
- U^c– the heat transfer coefficient in *HE-c* [W/(m^2 ^{0}C)];
- τ^c– the time for heating of the cold fluid in *HE-c* [s];
- M^h– the mass of the fluid to be cooled [kg];
- cp^h– the specific heat capacity of the fluid to be cooled [J/(kg. ^{0}C)];
- T^{h0}– the temperature of the fluid to be cooled [^{0}C];
- A^h– the heat exchange surface of *HE- h* [m^2];
- U^h – the heat transfer coefficient in *HE-h* [W/(m^2 ^{0}C)];
- τ^h– the time for cooling of the hot fluid in *HE-h* [s].

The purpose of the mathematical description is to determine the temperatures at the end of the processes of heating and cooling at outlets of the heat exchangers as well as the initial temperatures T^{mh0} and T^{mc0} in the heat storage tank.

INCLUSION OF MODELS WITHIN A TWO-STAGE STOCHASTIC OPTIMIZATION PROBLEM

The proposed general framework for efficient energy integration of batch systems is suitable for inclusion in a stochastic optimization framework because:
- the uncertain parameters of the integrated flows are independent of each other, since the temperatures of the hot streams at the outlet are product of previous system charges and they have not direct relation to the temperature of the raw sludge streams to be heated;
- the integration processes are carried out at stopped bioreactors, which allows the system to be considered as an open during its mathematical modeling (i.e. the processes in the reactors are not discussed).

Energy efficincy analysis of energy integration at the boundaries of the stochastic space

In order to determine the efficiency of the proposed integration scheme, an analysis of the energy integration efficiency at the boundaries of the stochastic space was made and the temperature range within which the temperatures of heated raw sludge at the end of the integration process can vary was determined. The boundaries of stochastic space determine the space in which uncertain data vary. Conditionally, it can be interpreted as a hyper-rectangle with vertices defined by the possible combinations of the lower and upper boundaries of the uncertain data. Their number is equal to 2^N, where N is the number of uncertain parameters.

For the ATAD systems, the uncertainties which have the most significant impact on sustainable operation are:
- Volumes of daily feeded / treated sludge: 12–20 m^3,
- Temperatures of feeded sludge: 5.6–20.2^{o}C,
- Temperatures of outlet treated sludge: 54.5–68.1^{o}C.

Thus, for the ATAD system under consideration, the number of vertices of the hyper rectangle is 8, where each of them represents a combination of the boundary values of the uncertain parameters and can be interpreted as a separate scenario. The main purpose of the analysis pertaining to the energy integration efficiency at the boundaries of stochastic space is to answer the question – „What is the temperature range within which the temperatures of heated raw sludge at the end of the integration process can vary?" For this purpose, mathematical models for the storage of „heat" and „cold" in batch production systems using one *(M1)* and two *(M2)* heat storage tanks should be included within deterministic optimization problems. The latter should be solved for each scenario vertex at an optimization criterion maximum temperature of the heated sludge outgoing from the heat exchanger *HE-c*. The results obtained determine the highest temperatures of the heated sludge, outgoing from heat exchanger

HE-c. It was found that the reached temperatures of heated sludge vary widely. In the case of operation of one heat storage tank, the lowest temperature to which the sludge may be preheated is 18.7°C. When the system operates with two heat storage tanks, it is 23.8°C. These temperatures determine the lower boundary of each of the substructures efficiency within the integration framework. These temperatures should be included as constraints in the stochastic optimization problem to provide efficient heat utilization during the integration process. Conditionally, these constraints are called *"integration efficiency constraints"*.

Framework of the stochastic optimization problem

The stochastic optimization problem combines the paradigm related to the allocation of the optimal resources with modeling of the stochastic parameters. Therefore, in order to obtain solutions of the stochastic optimization problem, it is necessary to know the following:

- how the stochastic space (space of uncertain parameters) will be approximated;
- how the optimization process will be organized on this space, i.e. when decisions will be made regarding the determination of uncertain parameters;
- which optimization technique will be applied.

Aproximated stochastic space

A widely used approach for stochastic space approximation is by generating many scenarios. *A* scenario in a stochastic model corresponds to any complete set of fixed, for all uncertain parameters, values, with a fixed probability of its realization. Only one set of scenarios is used to solve a stochastic model for which the sum of the fixed probabilities is 1. Discretization of uncertain space by generating scenarios is usually related to the representation of the stochastic optimization problem in terms of its deterministic equivalent of multi-scenario two-stage stochastic programming. This leads to the formulation of an optimization problem, not on the whole space, but on its representative subset of scenarios, for which it is proved that approximate the stochastic space well. The selection of scenarios should be made in such a way that the values of the uncertain parameters in each scenario have equal probability of appearence p_s, and the sume of probabilities of selected scenarios to be equal of 1.

In this study, the Monte Carlo method was used for generating scenarios. In it, independent pseudo-random samples are first generated to approximate a uniform distribution, and then the specific values of the probability distribution are created by inverse transformation of the cumulative distribution function, [10]. By applying the method, many stochastic parameters are obtained: the volume of feeded and treated sludge; the temperature of incoming cold raw sludge; the temperature of discharged stabilized hot sludge which appear with equal probability. They form a set of scenarios. From it, by defining a special optimization problem, a subset *S* is selected, with a minimum number for which the sum of their probabilities is 1.

Dividing of variables

According to the two-stage stochastic programming paradigm, variables are divided into two subsets – *variables* related to the first stage and *variables* related to the second stage. During the problem solution for redesign of an energy integrated ATAD system using a superstructure, decisions are made in the first stage related to major capital costs. They are determined by the selected integration substructure. An independent binary variable ε is introduced to manage the substructure selection, as follows:

$$\varepsilon = \begin{cases} 1\text{- if substructure with one heat storage tank is selected} \\ 0\text{- otherwise;} \end{cases}$$

The selection of a substructure with two heat storage tanks is made using the expression (1 – ε).

The sizes of the main equipment (heat exchanger surface for the heat exchangers *HE-c* and *HE-h* and the operationg volume of the intermediate hot / cold fluid) are the other selected *independent variables* for the first stage:

- A^c– heat exchanger surface for heat exchanger *HE-c* [m^2];
- A^h– heat exchanger surface for heat exchanger *HE-h* [m^2];
- V^m– operating volume of the intermediate hot / cold agent [m^3].

The second stage solutions must provide a feasibility of integration by determining the appropriate times for fluid transport. They determine the fluid transport rates for each scenario *s*, the necessary pumps are selected and the electricity cost for the maintenance of the system is determined. Therefore, times as *independent variables* for the second stage are determined:

τ_s^c / τ_s^h – for heating / cooling fluids in a heat exchanger *HE-c/ HE-h* [s] and for each one scenario $-s,\ \forall s, s \in S$.

With the exception of the binary variable, all other independent variables, both for the first and second stages, are continuous with boundaries:

$$A\min^c \le A^c \le A\max^c, \qquad A\min^h \le A^h \le A\max^h,$$

$$\tau\min^h \le \tau_s^h \le \tau\max^h, \qquad \tau\min^c \le \tau_s^c \le \tau\max^c$$

$$V\min^m \le V^m \le V\max^m$$

за $\forall s, s \in S$

The boundaries of the variables for the first stage should determine these regions of change in the characteristics of the main equipment (heat exchange surfaces and the operating volume of the heat storage tank), which are affected by the change in the stochastic parameters. For this purpose, a deterministic optimization problem is formulated for each vertex of the stochastic space, which includes the model of heat integration of flows in the ATAD system, constraints of the physical feasibility of heat exchange and a constraint of the efficiency of integration. Minimizing the capital costs for the main equipment is selected as an optimization criterion. The solution of the optimization problem thus formulated, for each scenario vertex of the stochastic space, determines the size of the main equipment at which the capital costs are minimal. They are used to select the boundaries of variation of values for the main equipment.

Mathematical models, constraints and objective function

The *M1* and *M2* mathematical models (in the case of one common and two separate heat storage tanks) are reformulated in terms of two-stage stochastic programming so that they are feasible for each scenario s, $s \in S$. Therefore, all temperatures in the integration schemes are defined as functions of the variables of the first and second stages, i.e. as functions of $\{A^c, A^h, M^m, \tau_s^c, \tau_s^h\}$, where $M^m = V^m.\rho^m$ [kg].

One heat storage –M1 model	***Two heat storages –M2 model***
ε. ***M1$_s$***	(1-ε). ***M2$_s$***
Heating part ***Temperatures at inlets and outles of heat exchanger HE-c***	
For a scenario $s \Rightarrow \{T_s^{c0}, T_s^{h0}, M_s\}$, $M_s = V_s.\rho$ [kg], $\forall s, s \in S$, cold fluid enters into heat exchanger *HE-c* with temperature T_s^{c0}, which is known, and after a time τ_s^c leaves with a temperature T_s^{c1}	
$T^{c1}(\tau_s^c) = \{T_s^{c0} + [T^{mh}(\tau_s^c) - T_s^{c0}\ ].R_s^c.\Phi e_s^c\}.\varepsilon$, where $R_s^c = \frac{w_s^{mh}.cp^m}{w_s^c.cp^c}$, $w_s^c = \frac{M_s}{\tau_s^c}$ [kg/s], $w_s^{mh} = \frac{M^m}{\tau_s^c}$ [kg/s], $\Phi e_s^c = \frac{1-\exp(-y_s^c.U^c.A^c)}{1-R_s^c.\exp(-y_s^c.U^c.A^c)}$ $y_s^c = \frac{1}{w_s^{mh}.cp^m} - \frac{1}{w_s^c.cp^c}$.	$T_s^{c1} = \{T_s^{c0} + (T_s^{mh0} - T_s^{c0})R_s^c\Phi e_s^c\}\ (1-\varepsilon)$ where $R_s^c = \frac{w_s^{mh}.cp^m}{w_s^c.cp^c}$, $w_s^c = \frac{M_s}{\tau_s^c}$ [kg/s], $w_s^{mh} = \frac{M^m}{\tau_s^c}$ [kg/s], $\Phi e_s^c = \frac{1-\exp(-y_s^c.U^c.A^c)}{1-R_s^c.\exp(-y_s^c.U^c.A^c)}$ $y_s^c = \frac{1}{w_s^{mh}.cp^m} - \frac{1}{w_s^c.cp^c}$

<table>
<tr><th>One heat storage –M1 model</th><th>Two heat storages –M2 model</th></tr>
<tr><td colspan="2">The temperatures of the hot intermediate fluid at inlet T_s^{mh} and at outlet T_s^{mh1} of HE-c, at the end of the heatexchange process τ_s^c are:</td></tr>
<tr><td>$T^{mh}(\tau_s^c)=\left\{T_s^{c0}+\left(T_s^{mh0}-T_s^{c0}\right).\exp\left(-G_s^{mh}.\Phi e_s^c.\tau_s^c\right)\right\}\ \varepsilon$
where
$G_s^{mh}=\dfrac{w_s^{mh}}{M^m}$ [sek^{-1}];</td><td>$T_s^{mh}=T_s^{mh0}\left(1-\varepsilon\right)$</td></tr>
<tr><td>$T^{mh1}(\tau_s^c)=\left\{T^{mh}(\tau_s^c)-\left(T^{mh}(\tau_s^c)-T_s^{c0}\right).\Phi e_s^c\right\}\ \varepsilon$,</td><td>$T_s^{mh1}=\left\{T_s^{mh0}-\left(T_s^{mh0}-T_s^{c0}\right)\Phi e_s^c\right\}\left(1-\varepsilon\right)$</td></tr>
<tr><td colspan="2">Cooling part
Temperatures at inlets and outles of heatexchanger HE-h</td></tr>
<tr><td colspan="2">Hot fluid enters into heat exchanger HE-h with a temperature T_s^{h0}, which is known, and at the end of the heat exchange process τ_s^h it is T_s^{h1}</td></tr>
<tr><td>$T^{h1}(\tau_s^h)=\left\{T_s^{h0}-\left(T_s^{h0}-T^{ms}(\tau_s^h)\right).\Phi e_s^h\right\}\ \varepsilon$
where
$R_s^h=\dfrac{w_s^h.cp^h}{w_s^{mc}.cp^m}$, $w_s^h=\dfrac{M_s}{\tau_s^h}$, [kg/s],
$w_s^{mc}=\dfrac{M^m}{\tau_s^h}$ [kg/s],
$\Phi e_s^h=\dfrac{1-\exp\left(-y_s^h.U^h.A^h\right)}{1-R_s^h.\exp\left(-y_s^h.U^h.A^h\right)}$
$y_s^h=\dfrac{1}{w_s^h.cp^h}-\dfrac{1}{w_s^{mc}.cp^m}$</td><td>$T_s^{h1}=\left\{T_s^{h0}-\left(T_s^{h0}-T_s^{mc0}\right)\Phi e_s^h\right\}\left(1-\varepsilon\right)$
where
$R_s^h=\dfrac{w_s^h.cp^h}{w_s^{mc}.cp^m}$, $w_s^h=\dfrac{M_s}{\tau_s^h}$, [kg/s],
$w_s^{mc}=\dfrac{M^m}{\tau_s^h}$ [kg/s],
$\Phi e_s^h=\dfrac{1-\exp\left(-y_s^h.U^h.A^h\right)}{1-R_s^h.\exp\left(-y_s^h.U^h.A^h\right)}$
$y_s^h=\dfrac{1}{w_s^h.cp^h}-\dfrac{1}{w_s^{mc}.cp^m}$</td></tr>
<tr><td colspan="2">The temperature of cooling intermediate fluid at inlet of the heat exchanger at a moment τ_s^h is T_s^{mc} and at outlet it is T_s^{mc1}</td></tr>
<tr><td>$T^{mc}(\tau_s^h)=\left\{T_s^{h0}+\left(T_s^{mc0}-T_s^{h0}\right).\exp\left(-R_s^h.\Phi e_s^h.G_s^{mc}.\tau_s^h\right)\right\}\ \varepsilon$
where
$G_s^{mc}=\dfrac{w_s^{mc}}{M^m}$ [s^{-1}].</td><td>$T_s^{mc}=T_s^{mc0}\left(1-\varepsilon\right)$</td></tr>
<tr><td>$T^{mc1}(\tau_s^h)=\left\{T_s^{mc}(\tau_s^h)+\left(T_s^{h0}-T^{mc}(\tau_s^h)\right).R_s^h.\Phi e_s^h\right\}\ \varepsilon$</td><td>$T_s^{mc1}=\left\{T_s^{mc0}+\left(T_s^{h0}-T_s^{mc0}\right)R_s^h\Phi e_s^h\right\}\left(1-\varepsilon\right)$</td></tr>
</table>

One heat storage –M1 model	***Two heat storages –M2 model***
Heat storage tanks T_s^{mh0} and T_s^{mc0} are initial "hot" temperature of the intermediate fluid in the heat storage tank, reached at the end of the cooling process of the hot part of the system and initial "cold" temperature of the intermediate fluid, reached at the end of the heating process of the cold part of the system	
$T_s^{mh0} = \frac{b_s^{22} + b_s^{12} b_s^{21}}{1 - b_s^{11} b_s^{21}} . \varepsilon$ $T_s^{mc0} = \frac{b_s^{12} - b_s^{11} b_s^{22}}{1 - b_s^{11} b_s^{21}} . \varepsilon$ $b_s^{11} = \exp(-G_s^{mh} \Phi e_s^c \tau_s^c);$ $b_s^{12} = \left[1 - \exp\left(-G_s^{mh} \Phi e_s^c \tau_s^c\right)\right] T_s^{c0},$ $b_s^{21} = \exp(-R_s^h \Phi e_s^h G_s^{mc} \tau_s^h);$ $b_s^{22} = \left[1 - \exp\left(-R_s^h \Phi e_s^h G_s^{mc} \tau_s^h\right)\right] T_s^{h0}.$	$T_s^{mh0} = \frac{\Phi e_s^c \left(R_s^h \Phi e_s^h - 1\right) T_s^{c0} - R_s^h \Phi e_s^h T_s^{h0}}{\left(R_s^h \Phi e_s^h - 1\right)\left(\Phi e_s^c - 1\right) - 1} (1 - \varepsilon)$ $T_s^{mc0} = \frac{\left(\Phi e_s^c - 1\right) R_s^h \Phi e_s^h T_s^{h0} - \Phi e_s^c T_s^{c0}}{\left(R_s^h \Phi e_s^h - 1\right)\left(\Phi e_s^c - 1\right) - 1} (1 - \varepsilon)$

The inclusion of *M1* or *M2* in the optimization framework depends entirely on the chosen integration substructure, i.e.ε.

The models are complemented by following constraints for:

- *feasibility of heat exchange in heat exchangers*.

Their purpose is not to allow the temperatures of the inlet and outlet fluids at the end of each of the heat exchangers to cross.

$$\Delta T_s^c = \min\left\{\varepsilon\left[\left(T^{mh1}(\tau_s^c) - T_s^{c0}\right); \left(T^{mh}(\tau_s^c) - T_s^{c1}(\tau_s^c)\right)\right]\right\}$$
$$\Delta T_s^c = \min\left\{(1-\varepsilon)\left[\left(T_s^{mh1} - T_s^{c0}\right); \left(T_s^{mh} - T_s^{c1}\right)\right]\right\} \quad \forall s, s \in S \tag{1}$$

$$\Delta T_s^h = \min\left\{\varepsilon\left[\left(T_s^{h0} - T^{mc1}(\tau_s^h)\right), \left(T^{h1}(\tau_s^h) - T^{mc}(\tau_s^h)\right)\right]\right\},$$
$$\Delta T_s^h = \min\left\{(1-\varepsilon)\left[\left(T_s^{h0} - T_s^{mc1}\right), \left(T_s^{h1} - T_s^{mc}\right)\right]\right\} \quad \forall s, s \in S \tag{2}$$

$$\Delta T_s^c \geq \Delta T^{\min}, \quad \Delta T_s^h \geq \Delta T^{\min}, \ \forall s, s \in S \tag{3}$$

- *effective operation of the selected integration substructure*.

The purpose is for each scenario *S*, that the temperature of the heated raw sludge coming into the first bioreactor be higher than or equal to the temperature defining the lower boundary of integration efficiency.

$$T^{c1}(\tau_s^c) \geq T_{M1}^{ef}; \quad T_s^{c1} \geq T_{M2}^{ef} \quad \forall s, s \in S \tag{4}$$

- *values of the initial temperatures in the heat storage tanks*.

The purpose is not to allow the initial "cold" and "hot" temperatures in the heat storage tank to cross and to ensure sufficient temperature levels in the heat storage tank at the end of the heating/cooling processes so that subsequent heating and cooling processes are possible.

$$\varepsilon . T_s^{mh0} \geq T_s^{c0}, \quad (1-\varepsilon) . T_s^{mh0} \geq T_s^{c0}, \ \forall s, s \in S \tag{5}$$

$$\varepsilon . T_s^{mc0} \leq T_s^{h0}, \quad (1-\varepsilon) . T_s^{mc0} \leq T_s^{h0}, \ \forall s, s \in S \tag{6}$$

$$\varepsilon . T_s^{mh0} \geq \varepsilon . T_s^{mc0}, \quad (1-\varepsilon) . T_s^{mh0} \geq (1-\varepsilon) . T_s^{mc0}, \ \forall s, s \in S \tag{7}$$

The objective function includes the expected annual capital and operating costs. The capital cost is determined by the cost of the main equipment, i.e. heat exchangers and heat storage tank (s) in the selected integration substructure. Their sizes depend on the values of the variables in the first stage. The capital costs also include the costs of pumps that must be selected in such a way that they are able to serve each scenario and provide feasibility of the integration process. Their sizes depend on both the values of variables for the first stage and the values of variables for the second stage. The operating costs are determined by the electricity consumed annually for transporting the fluids in realization of each scenario. They also depend on the values of the variables for the first and second stages.

$$ATADCost = \frac{1}{\gamma}\{C(A^c) + C(A^h) + C(V^m).\varepsilon +$$
$$+ C(V^m)(1-\varepsilon) + C(PC_{s*}) + C(PH_{s**}) + C(PM_{s***})\} + \quad (8)$$
$$+ \varepsilon.\sum_{s=1}^{S} EN_s + (1-\varepsilon).\sum_{s=1}^{S} EN_s$$

$$\underset{A^c, A^h, V^m, \tau_s^c, \tau_s^h, \forall s, s\in S}{MIN} \quad ATADCost \quad (9)$$

Optimization results

Using the Monte Carlo method, the reduced samples were determined from the entire data set concerning to the corresponding values of the stochastic parameters $\{V\}$, $\{T^{c0}\}$, and $\{T^{h0}\}$ and the probabilities of their occurrence were determined. Using BASIC genetic algorithm [11], the defined stochastic optimization problem is solved many times for each scenarios set. For the purpose of integration, the solutions that were obtained use both one and two heat storage tanks. As expected, the solutions with the lowest price between 14300–16500 CU are with one heat storage tank while those with two heat storage tanks have a price between 16300 and 17200 CU.

The annual capital costs for redesign and operation of the ATAD system are listed in Table 1. Table 2 shows the values of the main and auxiliary equipment at which the respective solutions were obtained.

As can be seen from the results presented in Table 1, the expected annual costs of redesign and operation differ significantly. They are obtained at different values of the variables for the first stage (the surfaces of the two heat exchangers and the heat storage tank). The size of the auxiliary equipment, which must be able to handle all scenarios, is determined by those scenarios at which the transported flows have a maximum flow rate, i.e. depends on the variables for the first stage and the values of the variables for the second stage for the specific scenarios. The electricity cost to service the pumps is determined by the actual flow rate through which the respective fluids are transported in each individual scenario.

ANALYSIS AND VERIFICATION OF THE SOLUTIONS OBTAINED

The analysis of the temperature reached after integration of the incoming raw sludge shows that in the solutions with one heat storage tank it is about 18–20 ^{o}C, while in the presence of two heat storage tanks it is between 23–25 ^{o}C. In both cases, this results in a substantial reduction of the thermal shock in the first bioreactor stage and they reach close to the optimum operating temperatures of 55 ^{o}C and 65 ^{o}C in the bioreactors from the first and second stages.

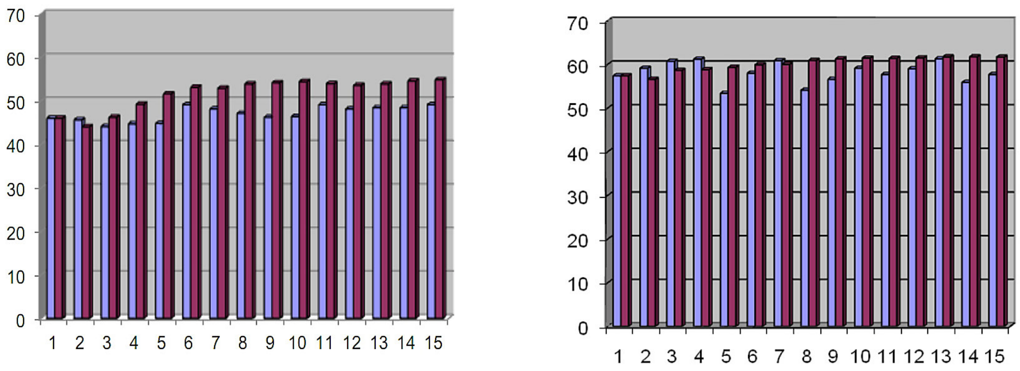
The purpose of verification of the energy-integrated ATAD system is to demonstrate, through the use of real-time data for a given period, how the energy integration affects the bioreactors operation, the temperatures and the sludge stabilization. It is also necessary to compare the

Table 1. Expected annual capital costs for redesign and operation of the ATAD system

Solution	Annual cost of redesign and operation [CU]	Capital cost for main equipment [CU]	Capital cost for auxiliary equipment [CU]	Operating costs [CU]
One heat storage tank	14330	8225	5808	296
Two heat storage tanks	16360	9826	5602	314

Table 2. Values of main and auxiliary equipment at which the relevant solutions are obtained

Solution	Heat exchangers [m^2]		Volume of intermediate fluid [m^3]	Pumps [m^3/h]		
	HE-c	HE-h	V	PC	PH	PM
One heat storage tank	25	45	30	26.6	53.2	81.5
Two heat storage tanks	30	60	33	26.6	53.2	90.7



a) Bioreactor 1 b) Bioreactor 2

Figure 3. Comparison between measured (blue) and calculated simulated (red) depth of thermal shock in a) Bioreactor 1 and b) Bioreactor 2 and calculated for the solution with one heat storage tank using the ANN model under the new temperature conditions of feeding flow

obtained values with the measured real values in order to evaluate the efficiency of energy integration for overcoming the effects of uncertain parameters. For the verification purpose, it is necessary to simulate numerically the operation of the energy-integrated ATAD system with included models of an industrial ATAD bioreactor. For this purpose, a model of an industrial ATAD bioreactor was created using the Artificial Neural Network (ANN) [5]. It allows, at specified values of feeding flow (volume, temperature, solids and volatile solids content) and the temperature in biorector during feeding, predicting: the depth of the thermal shock, the expected temperature at the end of the process and the degree of reduction. The best ANN model of the ATAD bioreactor, as well as the integration framework with the best solutions obtained, are combined in order to realize a numerical simulation of the operation of the energy-integrated ATAD system. An adequate transfer of data between the modules simulating the bioreactors and the energy integration module is provided. The simulation starts from the moment of realization of the data transfer from the module of second bioreactor to the integration module. A startup data set for the implementation of the first two batches in the bioreactor modules from which the process is to be initiated has been determined. The set (for a specified period) of the actual data of the ATAD feeding flow is also determined. As a result of the simulation, for the specified values of the ATAD feeding flow (volume, temperature, solids and volatile solids contents), it is shown how the temperature of the incoming flow changes after passing through the integration module and how this new temperature affects the thermal shock depth, the expected temperature at the end of the process, and degree of the volatile solids reduction in the two modules modeling the ATAD bioreactors from the first and second stages. The comparison was also made with the actual values of the relevant parameters in the bioreactors.

CONCLUSIONS

The present study proposes a methodology for energy efficiency and sustainability improvement of operating conditions of an ATAD municipal wastewater treatment system. An energy-integrated system of one and two heat storage tanks combined in a mathematical superstructure was proposed. The models were included within a two-stage stochastic optimization problem. An analysis and verification of the obtained solutions was made. From the results obtained, it can be concluded that the lowest capital and operating costs of the equipment are not always the best solution that provides sustainable operation of the ATAD system. The choice of equipment is a decision of the management team. The methodology can be applied to other energy-integrated batch production systems for the purpose of their energy efficiency and sustainability improvement.

Acknowledgments

The study has been carried out by the financial support of National Science Fund, Ministry of Education and Science of the Republic of Bulgaria, Contract № ДН07–14/15.12.16.

We thank our colleagues from the University of Limerick, Ireland who provided us with real scale data of ATAD system.

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