# MINLP Synthesis of Processes for the Production of Biogas from Organic and Animal Waste

**R. Drobež,[a] Z. Novak Pintarič,[b] B. Pahor,[c] and Z. Kravanja[b,*]**
[a] Scientific research centre Bistra Ptuj, Slovenski trg 6, SI-2250 Ptuj, Slovenia
[b] University of Maribor, Faculty of Chemistry and Chemical Engineering, Smetanova ul. 17, SI-2000, Maribor, Slovenia
[c] Perutnina Ptuj, Potrčeva 10, SI-2250 Ptuj, Slovenia

Original scientific paper
Received: June 9, 2009
Accepted: October 30, 2009

*Dedicated to the memory of Professor Dr. Valentin Koloini*

This paper describes a superstructure approach for the synthesis of biogas processes simultaneously with the selection of different process background alternatives. The superstructure consists of anaerobic fermentation under thermophilic or mesophilic conditions, including options for a rendering plant, with different organic and animal wastes from either existing or new plants, different water supplies, wastewater treatments and biogas usage options. An aggregated mathematical model with an economic objective function, formulated as a mixed-integer nonlinear programming (MINLP) problem, was developed. An industrial case study was applied to an existing large-scale meat company, in order to describe the mathematical model and illustrate the MINLP synthesis approach. The optimal solution indicates that significant benefit can be obtained if biogas processes are selected simultaneously with the selection of different process background alternatives thus yielding the optimal integration of biogas processes with their background.

*Key words:*
Biogas, optimization, animal waste

## Introduction

Animal waste from slaughterhouses and animal manure is often mishandled and underutilized, giving rise to serious environmental and economic problems. Meat companies usually convert slaughterhouse wastes of category III, e.g. bones, offals, and blood at their in rendering plants, into several products, e.g. meat and bone meal, which are used for the preparation of food for domestic animals. On the other hand, wastes of category II e.g. poultry manure, may still be used for field fertilization. However, strict environmental, veterinary and medical regulations demand serious changes in the legislation, e.g. directives to protect underground water by restricting the use of nitrate, and it is only the matter of time until this field fertilization is forbidden. Therefore, an efficient, economical and sustainable solution is needed, preferably one which converts wastes into valuable products.[1,2] Biogas production[3,4] is one of them, since biogas can be used for heat, electricity, and liquid fuel production. In most cases the biogas is used for combined heat and power (CHP) generation.[5]

* Author to whom correspondence should be addressed.
E-mail: zdravko.kravanja@uni-mb.si

Anaerobic digestion is the most commonly-applied process for the treatment of animal manure, and organic waste from the agricultural and food industries.[6,7] It reduces the pollution of air, water and soil, and produces methane. Anaerobic digestion is a natural biological process in which organic matter is degraded by microorganisms into a mixture of methane and carbon dioxide under different anaerobic conditions, mesophilic and thermophilic being the most commonly used.[8,9,10] It is well-known that the thermophilic is more efficient than the mesophilic in terms of retention time, loading rate, and nominal biogas production but it needs a higher energy input, more expensive technology, and greater sensitivity to operating and environmental variables, which make the process more problematic than mesophilic digestion.[11,12] Since the thermophilic process enables operation at a higher loading rate,[13] the increased production of methane and nutrient-rich fertilizers can provide substantial financial incomes for meat companies.

In open literature, several papers have addressed the optimization of biogas processes. Most of them deal with the experimental determination of optimal values for the most influential parameters, e.g.,[10,12,14,15,16] one of them also discusses an optimal reactor configuration design.[10] Among the remaining papers, different simulation models are presented for the performance prediction and optimization of biogas plants,[17,18] including an energy balance model for the dynamic calculation of energy production[19] and an investment cost correlation model.[18] Gielen *et al.*[20] also addressed the modelling and optimization of biomass policies for $CO_2$ emission reduction. However, to our knowledge, almost no model has been developed so far for the selection of optimal biogas processes, especially when considering different organic and animal wastes and different process background alternatives.

The goal of this research was the development of such a mathematical programming model in aggregated form, for an optimal synthesis of biogas processes. Due to the presence of discrete and continuous decisions, the superstructure approach to the synthesis was systematically applied. It consists of three steps:

a) definition of the superstructure, comprised of various process and process background alternatives,

b) development of a mixed-integer model formulation for the defined superstructure, and

c) solution of the developed mixed-integer nonlinear programming (MINLP) problem.[21,22,23]

The paper is organized as follows: A more general biogas superstructure and a more detailed superstructure, the latter being applied to an existing industrial case study, first introduced in Section 2. A mathematical model formulated as an MINLP problem is then presented in Section 3, for the preliminary selection of an optimal process for the utilization of animal and other bio-waste. The solution of the case study is presented and discussed in Section 4, followed by the conclusions in Section 5.

## Biogas process superstructure

Different alternatives can be embedded in the superstructure in order to compete for an optimal solution. Let us first consider a more general superstructure given, as in Fig. 1. It consists of different biogas processing options and different background alternatives by which organic waste can be converted into precious products. As for the biogas processing option, one can typically consider thermophilic or mesophilic processes while, for process background alternatives, there are different water supplies, wastewater treatment, and other alternatives, e.g. waste can be taken from existing, new or reconstructed farms, water can be supplied either as freshwater or industrial wastewater, the produced biogas can be utilized, e.g. directly in a combined heat and power plant (CHP) or purified and used as vehicle fuel. In addition, different

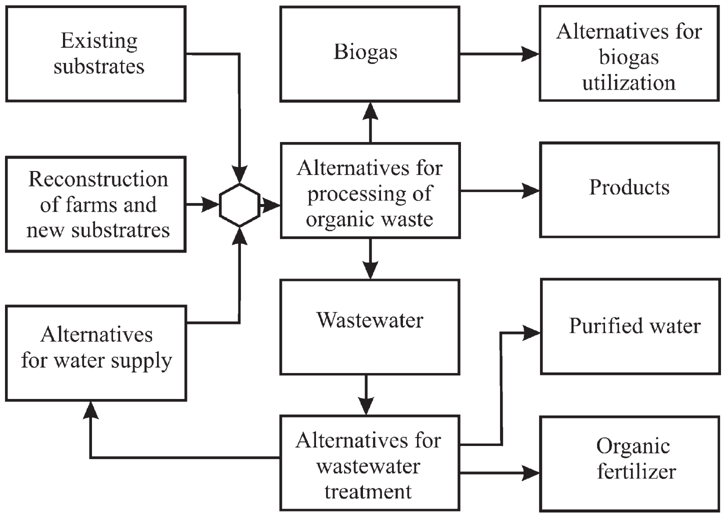



Fig. 1 – *A more general superstructure of animal and other bio-waste utilization*

by-products from organic waste utilization, such as meat and bone meal, can be produced and sold as food for domestic animals. According to the superstructure, the wastewater from biogas production can be re-used during the same production process, after purification by different treatment units. As a by-product from these treatments, liquid organic fertilizer can be produced by which minerals and other components can be recycled back to the fields in order to complete the cycle.

Based on the described more general superstructure a more specific superstructure, applied to an existing large-scale meat company, is derived (Fig. 2). The aim is to obtain an answer to several questions and dilemmas important for the management of the company:

a) What is the optimal choice for the processing of animal manure and organic waste from the food industry: biogas production by anaerobic fermentation at mesophilic or thermophilic condition, with or without a combination of the rendering plant?

b) According to long-term market trends, the price of pig meat is decreasing whilst poultry meat is increasing. So, what is the optimal choice for the meat company? Should they reconstruct the existing pig farm and continue with pork meat production or adapt it and start producing poultry as the company's main activity?

c) If an existing pig farm is adapted, it will be necessary to provide an additional water source to fulfill all the production requirements. Water demands can be satisfied by freshwater from a local well or from the meat industry as an industrial wastewater. In addition, the industrial wastewater can be transported by cisterns or a pressurized sewage pipeline. Although the second option is sustain-

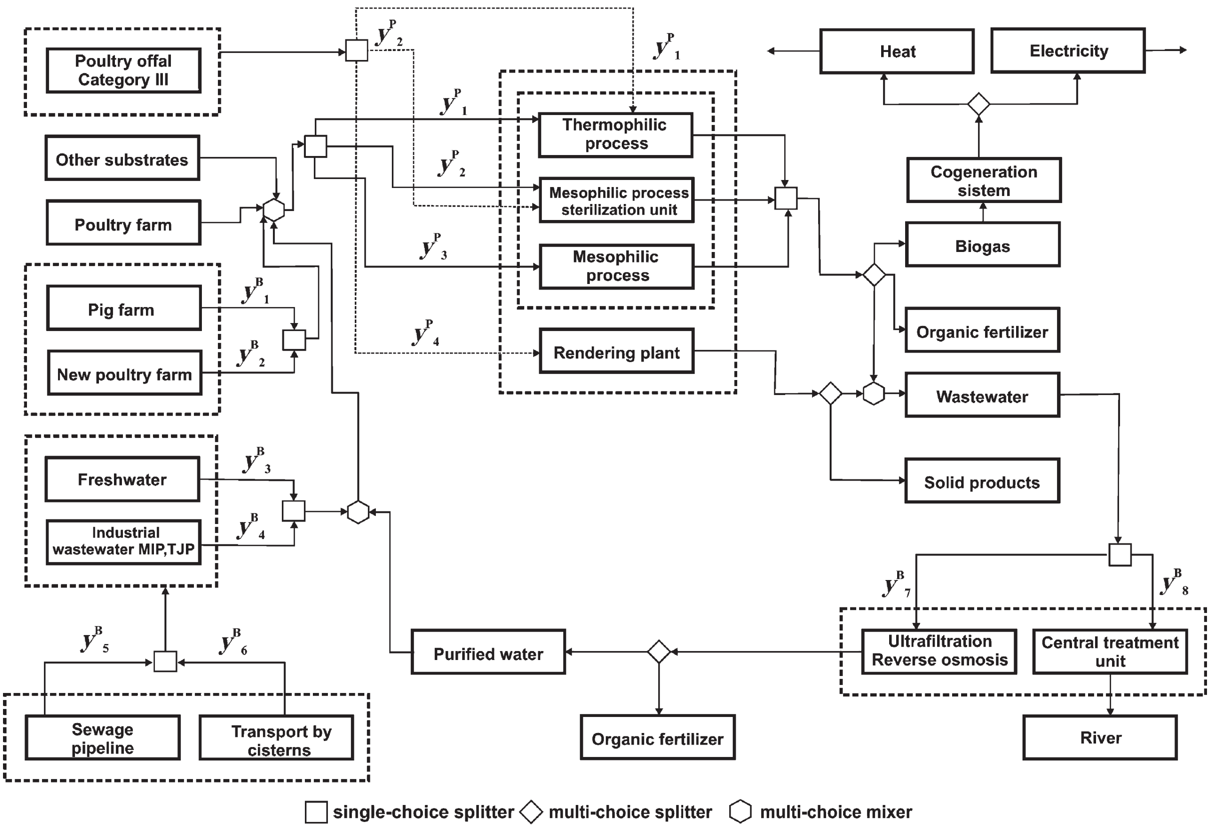



Fig. 2 – *Superstructure for selecting the optimal processing system for the industrial case study*

able from the environmental point of view, it may not satisfy the economical criteria. It should be noted, that since the freshwater source is located near a potential location for a biogas production plant, the pumping and transportation cost of freshwater may be low compared to the transportation cost of industrial wastewater.

d) Other alternatives are about the selection of appropriate wastewater treatment processes, depending on the water network type, which can be either open or closed. In the case of an open-circuit water system, the wastewater would be treated in a central treatment unit and, after purification, discharged into the environment. In the closed water system with technologies for re-using wastewater, the wastewater would be treated by ultrafiltation and reverse osmosis, and the purified wastewater permeate could be re-used during the biogas production process, while the concentrate could be sold as an organic fertilizer.

## Aggregated mathematical model for selecting of an optimal biogas process

The next step in the superstructure approach is the modelling of a given superstructure. Since, in our case, the more general superstructure of Fig. 1 is too general to be modelled, we have applied the modelling to the superstructure of an industrial case study (Fig. 2). The model is formulated as a mixed-integer nonlinear programming (MINLP) problem for the selection of an optimal process for processing animal and other bio-waste. It is formulated in an aggregated, compact form where the net present worth (NPW) is defined as an objective function with concave investment cost correlations, subject only to mass balances, simplified design equations and simplified performance relationships without reaction kinetics and time constraints. Also, detailed specifications and simultaneous heat integration between process and process background alternatives have not been taken into consideration. It is assumed that daily available quantities of substrates are given as mean values, constant over the whole year. Before presenting the model, let us first define the following sets and binary variables:

– Set $I$ for the inlet substrates and water supply, defined in Table 1, $I = \{1,\dots,25\}$, and subsets:

– $I_1$ for the slaughterhouse waste of category III, $I_1 = \{4,\dots,11\}$,

– $I_2$ for the inlet substrates from the pig farm, $I_2 = \{1,2,3\}$,

– $I_3$ for the potential inlet substrates from the new poultry farm, $I_3 = \{12,\dots,16\}$,

– $I_4$ for the freshwater, $I_4 = \{16\}$,
– $I_5$ for the industrial wastewater, $I_5 = \{14,15\}$, and
– $I_6$ for the substrates purchased on the market, $I_6 = \{16,23\}$.

– Set $K$ for the solid product from the rendering plant, $K = \{1,2,3\}$:

1 = meat meal,

2 = animal fat,

3 = bone meal.

– Set $J$ for the production processes, $J = \{1,2,3,4\}$, and subsets:
– $J_1$ for the anaerobic conversion process, $J_1 = \{1,2,3\}$,
– $J_2$ for the rendering plant, $J_2 = \{4\}$,
– $J_3$ for processes which can utilized the slaughterhouse waste of category III, $J_3 = \{1,2,4\}$; where:

1 = thermophilic process,

2 = mesophilic process using a sterilization unit,

3 = the mesophilic process without a sterilization unit,

4 = rendering plant.

– Set $L$ for the remaining background alternatives, $L = \{1,\dots,8\}$, and subsets:
– $L_1$ for alternatives which need some additional investment, $L_1 = \{1,2,5,7\}$,
– $L_2$ for an existing pig farm, $L_2 = \{1\}$,
– $L_3$ for a new poultry farm, $L_3 = \{2\}$,
– $L_4$ for water supply as freshwater, $L_4 = \{3\}$,
– $L_5$ for water supply as industrial wastewater, $L_5 = \{4\}$,
– $L_6$ for industrial wastewater transportation alternatives, $L_6 = \{5,6\}$,
– $L_7$ for wastewater treatment alternatives, $L_7 = \{7,8\}$,
– $L_8$ for a closed water system, $L_8 = \{7\}$,
– $L_9$ for an open water system $L_9 = \{8\}$; where:

1 = the reconstruction of an existing pig farm,

2 = the adaptation of an existing pig farm to a new poultry farm,

3 = water supply as freshwater,

4 = water supply as industrial wastewater,

5 = transportation of industrial wastewater by a pressure sewage pipeline,

6 = transportation of industrial wastewater by cisterns,

7 = a closed water system with ultrafiltration and reverse osmosis,

8 = an open water system with a central wastewater treatment unit.

Binary variables

– $y_j^{\mathrm{P}}$ binary variable for the selection of optimal production process $j$,

– $y_l^{\mathrm{B}}$ binary variable for the selection of optimal remaining background alternative $l$.

## Mass balances and biogas production

### *Mass balances for biogas processes*

In the mass balance of biogas production, the sum of the mass flow-rates of substrates to process $j$, plus the sum of the mass flow-rates of the recirculated wastewater from the wastewater treatment unit, should be equal to the sum of the out-flowing mass flow-rate of biogas and residue from the process:

$$\sum_{i \in I} q_{m_{i,j}} + \sum_{l \in L_8} q_{m_{j,l}}^{\mathrm{RWW}} = q_{v_j}^{\mathrm{BG}} \cdot \rho^{\mathrm{BG}} + q_{m_j}^{\mathrm{R}}, \quad \forall j \in J_1 \quad (1)$$

where $q_{m_{i,j}}$/(kg d$^{-1}$) denotes the mass flow-rate of substrate $i$ in process $j$, $q_{m_{j,l}}^{\mathrm{RWW}}$/(kg d$^{-1}$) the mass flow-rate of recirculated wastewater from the purification system $l$ to process $j$, $q_{v_j}^{\mathrm{BG}}$/(m$^3$ d$^{-1}$) the volume flow-rate of biogas produced in process $j$, $\rho^{\mathrm{BG}}$/(kg m$^{-3}$) the density of the biogas, and $q_{m_j}^{\mathrm{R}}$/(kg d$^{-1}$) the mass flow-rate of the residue leaving process $j$.

The biogas volume flow-rate production is proportional to the mass flow-rate of substrate $i$ to process $j$, and the mass fraction of VSS in substrate $i$:

$$q_{v_j}^{\mathrm{BG}} = f_j \cdot \left[ \sum_{i \in I} q_{m_{i,j}} \cdot w_i^{\mathrm{VSS}} \cdot S_i^{\mathrm{BG}} \right] \quad \forall j \in J_1 \quad (2)$$

where $f_j$ is the factor of biogas production for process $j$, $w_i^{\mathrm{VSS}}$ is the mass fraction of VSS in substrate $i$ and $S_i^{\mathrm{BG}}$/(m$^3$ kg$^{-1}$) is the specific biogas production from substrate $i$ per unit of VSS, under standard conditions.

### *Mass balance for the production of solid product in a rendering plant ($j \in J_2$)*

In the mass balance for the production of a solid product, the sum of mass flow-rates of substrates to the plant should be equal to the sum of out-flowing mass flow-rates of solid products ($q_{m_{j,k}}^{\mathrm{SP}}$), and residue from the process:

$$\sum_{i \in I} q_{m_{i,j}} = \sum_{k \in K} q_{m_{j,k}}^{\mathrm{SP}} + q_{m_j}^{\mathrm{R}} \quad \forall j \in J_2 \quad (3)$$

where $q_{m_{j,k}}^{\mathrm{SP}}$/(kg d$^{-1}$) denotes the mass flow-rate of solid product $k$ in process $j$.

The production of solid product $k$ by process $j$ ($q_{m_{j,k}}^{\mathrm{SP}}$) is further defined as follows:

$$q_{m_{j,k}}^{\mathrm{SP}} = w_k^{\mathrm{SP}} \cdot \sum_{i \in I_1} q_{m_{i,j}} \quad \forall j \in J_2, k \in K \quad (4)$$

where $w_k^{\mathrm{SP}}$ is the mass fraction of solid product $k$ for the rendering plant.

The mass flow-rate of substrate $i$ ($q_{m_i}^{\mathrm{S}}$) is further defined as:

$$q_{m_i}^{\mathrm{S}} = \sum_{j \in J} q_{m_{i,j}} \qquad \forall i \in I \quad (5)$$

where $q_{m_i}^{\mathrm{S}}$/(kg d$^{-1}$) denotes the mass-flow rate of substrate $i$.

*Mass balance for wastewater*

The mass flow-rate of wastewater from process $j$ to wastewater treatment systems $l$ ($q_{m_{j,l}}^{\mathrm{WW}}$/(kg d$^{-1}$)) is defined as:

$$q_{m_{j,l}}^{\mathrm{WW}} = q_{m_{j,l}}^{\mathrm{WWC}} + q_{m_{j,l}}^{\mathrm{WWO}} \quad \forall j \in J_1, l \in L_7 \quad (6)$$

where $q_{m_{j,l}}^{\mathrm{WWC}}$/(kg d$^{-1}$) is the mass flow-rate of wastewater from process $j$ in the closed water system ($l \in L_8$), and $q_{m_{j,l}}^{\mathrm{WWO}}$/(kg d$^{-1}$) is the mass flow-rate of wastewater from process $j$ in the open water system ($l \in L_9$).

The mass flow-rate of wastewater from process $j$ to the wastewater treatment systems $l$ is further defined as follows:

$$\sum_{l \in L_7} q_{m_{j,l}}^{\mathrm{WW}} = w^{\mathrm{WW}} \cdot \left[ \sum_{i \in I} q_{m_{i,j}} \cdot (1 - w_i^{\mathrm{DMC}}) + \right.$$
$$\left. + \sum_{l \in L_8} q_{m_{j,l}}^{\mathrm{RWW}} \cdot (1 - w_{j,l}^{\mathrm{DMC,RWW}}) \right] \qquad \forall j \in J_1 \quad (7)$$

where $w^{\mathrm{WW}}$ denotes the overall mass fraction of wastewater, $w_i^{\mathrm{DMC}}$ the dry matter content of substrate $i$, and $w_{j,l}^{\mathrm{DMC,RWW}}$ the dry matter content of the recirculated wastewater. Note that, in this case study, ultrafiltration and reverse osmosis belong to the closed water system and the mass flow-rate of wastewater from process $j$ belongs to the closed water network ($l \in L_8$), $q_{m_{j,l}}^{\mathrm{WWC}}$/(kg d$^{-1}$) defined as:

$$q_{m_{j,l}}^{\mathrm{WWC}} = q_{m_{j,l}}^{\mathrm{WW}} \qquad \forall j \in J_1, l \in L_8 \quad (8)$$

On the other hand, the central treatment unit belongs to the open water system. The mass flow-rate of the wastewater from process $j$ to the open water system ($l \in L_9$), $q_{m_{j,l}}^{\mathrm{WWO}}$/(kg d$^{-1}$) is then:

$$q_{m_{j,l}}^{\mathrm{WWO}} = q_{m_{j,l}}^{\mathrm{WW}} \qquad \forall j \in J_1, l \in L_9 \quad (9)$$

In addition, the mass flow-rate of wastewater from process $j$ to the closed water network ($q_{m_{j,l}}^{\mathrm{WWC}}$) is split into the mass flow-rate of wastewater after purification recirculated to process $j$, and the mass flow-rate of an organic fertilizer leaving process $j$ ($q_{m_{j,l}}^{\mathrm{OF}}$/(kg d$^{-1}$)):

$$q_{m_{j,l}}^{\mathrm{WWC}} = q_{m_{j,l}}^{\mathrm{RWW}} + q_{m_{j,l}}^{\mathrm{OF}} \quad \forall j \in J_1, l \in L_8 \quad (10)$$

where the mass flow-rate of the recirculated wastewater ($q_{m_{j,l}}^{\mathrm{RWW}}$) is further defined as:

$$q_{m_{j,l}}^{\mathrm{RWW}} = w_l^{\mathrm{RWW}} \cdot q_{m_{j,l}}^{\mathrm{WWC}} \quad \forall j \in J_1, l \in L_8 \quad (11)$$

$w_l^{\mathrm{RWW}}$ being the split fraction of the recirculated wastewater.

*Mass balance for industrial wastewater*

Water consumption, supplied by industrial wastewater ($q_{m_i}^{\mathrm{S}}$), ($i \in I_5$), should be equal to the sum of the mass flow-rates of transported industrial wastewater ($q_{m_{i,l}}^{\mathrm{T}}$/(kg d$^{-1}$)) by pressure sewage pipeline or cisterns:

$$q_{m_i}^{\mathrm{S}} = \sum_{l \in L_6} q_{m_{i,l}}^{\mathrm{T}} \qquad \forall i \in I_5 \quad (12)$$

## Logical and other constraints for mass flow rates

*Constraints for substrates*

Each mass flow rate of substrate $i$ flowing to process $j$ is either limited by the available daily amount of the substrate if the process is selected ($y_j^{\mathrm{P}} = 1$) or set to zero value if the process is rejected ($y_j^{\mathrm{P}} = 0$):

$$q_{m_{i,j}} \ge q_{m_{i,j}}^{\mathrm{LO}} \cdot y_j^{\mathrm{P}} \qquad \forall i \in I, j \in J \quad (13)$$

$$q_{m_{i,j}} \le q_{m_{i,j}}^{\mathrm{UP}} \cdot y_j^{\mathrm{P}} \qquad \forall i \in I, j \in J \quad (14)$$

where $q_{m_{i,j}}^{\mathrm{LO}}$/(kg d$^{-1}$) and $q_{m_{i,j}}^{\mathrm{UP}}$/(kg d$^{-1}$) are the lower bounds of the required and upper bounds of available daily mass flow-rates of substrates $i$ ($i \in I$) for processes $j$ ($j \in J$), and $y_j^{\mathrm{P}}$ the binary variable for the selection of optimal production process $j$. It should be noted that the utilization of slaughterhouse waste of category III requires the use of a sterilization unit unless it is processed in the rendering plant.

The mass flow-rates of the inlet substrate $i$ for process $j$ from the pig farm ($i \in I_2$) and new poultry farm ($i \in I_3$), are similarly limited by:

$$q_{m_{i,j}} \le q_{m_{i,j}}^{\mathrm{UP}} \cdot y_l^{\mathrm{B}} \quad (\forall i \in I_2, j \in J_1, l \in L_2) \text{ and } (\forall i \in I_3, j \in J_1, l \in L_3) \qquad (15)$$

where $y_i^{\mathrm{B}}$ is a binary variable for the selection of the corresponding background alternative $l$. Constraints for the mass flow-rates of water supply as freshwater ($i \in I_4$) and industrial wastewater ($i \in I_5$) for process $j$ are given by:

$$q_{m_{i,j}} \le q_{m_{i,j}}^{\mathrm{UP}} \cdot y_l^{\mathrm{B}} \quad (\forall i \in I_4, j \in J_1, l \in I_4) \text{ and } (\forall i \in I_5, j \in J_1, l \in I_5) \qquad (16)$$

and the mass flow-rate of residue for process $j$ by:

$$q_{m_j}^{\mathrm{R}} \le q_{m_j}^{\mathrm{R,UP}} \cdot y_j^{\mathrm{P}} \qquad \forall j \in J \qquad (17)$$

where $q_{m_j}^{\mathrm{R,UP}}$/(kg d$^{-1}$) is an upper bound of the residue for process $j$.

Finally, the production of solid product $k$ is limited by the daily capacity of the rendering plant:

$$\sum_{k \in K} q_{m_{j,k}}^{\mathrm{SP}} \le \sum_{k \in K} q_{m_k}^{\mathrm{SP,UP}} \cdot y_j^{\mathrm{P}} \qquad \forall j \in J_2 \qquad (18)$$

where $q_{m_k}^{\mathrm{SP,UP}}$/(kg d$^{-1}$) denotes the daily capacity of the rendering plant for the production of solid product $k$.

*Logical constraints for biogas production*

Upper and lower bounding logical constraints for biogas production regarding process $j$ are given by the following inequalities:

$$q_{v_j}^{\mathrm{BG}} \ge q_{v_j}^{\mathrm{BG,LO}} \cdot y_j^{\mathrm{P}} \qquad \forall j \in J_1 \qquad (19)$$

$$q_{v_j}^{\mathrm{BG}} \le q_{v_j}^{\mathrm{BG,UP}} \cdot y_j^{\mathrm{P}} \qquad \forall j \in J_1 \qquad (20)$$

where $q_{v_j}^{\mathrm{BG,LO}}$/(kg d$^{-1}$) and $q_{v_j}^{\mathrm{BG,UP}}$/(kg d$^{-1}$) are the lower and upper bounds on the production of biogas by process $j$.

*Logical constraints for wastewater*

The mass flow-rate of wastewater from process $j$ to alternative treatment unit $l$ is limited by:

$$q_{m_{j,l}}^{\mathrm{WW}} \le q_{m_{j,l}}^{\mathrm{WW,UP}} \cdot y_j^{\mathrm{P}} \quad \forall j \in J_1, l \in L_7 \quad (21)$$

where $q_{m_{j,l}}^{\mathrm{WW,UP}}$/(kg d$^{-1}$) denotes an upper bound of wastewater from process $j$ to alternative treatment unit $l$.

Similarly, the mass flow-rate of recirculated wastewater flowing back to process $j$ is limited by:

$$q_{m_{j,l}}^{\mathrm{RWW}} \le q_{m_{j,l}}^{\mathrm{RWW,UP}} \cdot y_l^{\mathrm{B}} \quad \forall j \in J_1, l \in L_8 \qquad (22)$$

$q_{m_{j,l}}^{\mathrm{RWW,UP}}$/(kg d$^{-1}$) being an upper bound of wastewater recirculated to process $j$, and the mass flow-rate of an organic fertilizer for the process $j$ in the closed water treatment unit $l$ by:

$$q_{m_{j,l}}^{\mathrm{OF}} \le q_{m_{j,l}}^{\mathrm{OF,UP}} \cdot y_l^{\mathrm{B}} \quad \forall j \in J_1, l \in L_8 \qquad (23)$$

where $q_{m_{j,l}}^{\mathrm{OF,UP}}$/(kg d$^{-1}$) is an upper bound for an organic fertilizer.

Finally, the mass flow-rates of transported industrial wastewater, ($q_{m_{i,l}}^{\mathrm{T}}$) by pressure sewage pipeline or by cisterns are constrained by:

$$q_{m_{i,l}}^{\mathrm{T}} \le q_{m_{i,l}}^{\mathrm{T,UP}} \cdot y_l^{\mathrm{B}} \quad \forall i \in I_5, l \in L_6 \qquad (24)$$

where $q_{m_{i,l}}^{\mathrm{T,UP}}$/(kg d$^{-1}$) is an upper bound for the wastewater.

*Constraint for dry matter content*

Fermentation requires liquid media with 8 % dry matter content. Since input substrates usually have higher dry matter content than the required 8 %, the substrates have to be diluted by the process water:

$$\sum_{i \in I} q_{m_{i,j}} \cdot w_i^{\mathrm{DMC}} + \sum_{l \in L_8} q_{m_{j,l}}^{\mathrm{RWW}} \cdot w_{j,l}^{\mathrm{DMC,RWW}} = w^{\mathrm{RDMC}} \cdot \left[ \sum_{i \in I} q_{m_{i,j}} + \sum_{l \in L_8} q_{m_{j,l}}^{\mathrm{RWW}} \right] \quad \forall j \in J_1 \quad (25)$$

where $w^{\mathrm{RDMC}}$ is required dry matter content (0.08).

## Logical constraints for the selection of process and background alternatives

*Constraints for process alternatives*

The biogas can be produced either by thermophilic ($y_1^{\mathrm{P}} = 1$) or mesophilic processes, with ($y_2^{\mathrm{P}} = 1$) or without a sterilization unit ($y_3^{\mathrm{P}} = 1$):

$$y_1^{\mathrm{P}} + y_2^{\mathrm{P}} + y_3^{\mathrm{P}} = 1 \qquad (26)$$

*Logical constraints for process background alternatives*

Several logical constraints are added to explicitly model the existence/non–existence of background alternatives in the optimal solution. The exclusive or logical constraint for selection between reconstructing the existing pig farm ($y_1^{\mathrm{B}} = 1$) and adapting the existing pig farm to a poultry farm ($y_2^{\mathrm{B}} = 1$) is simply defined as follows:

$$y_1^{\mathrm{B}} + y_2^{\mathrm{B}} = 1 \qquad (27)$$

If reconstruction of the pig farm into a new poultry farm is selected ($y_2^{\mathrm{B}} = 1$), then it is necessary to supply some process water to the process. The process water demand can be satisfied by freshwater from a local well ($y_3^{\mathrm{B}} = 1$) or by industrial wastewater from the background meat industry ($y_4^{\mathrm{B}} = 1$):

$$y_3^{\mathrm{B}} + y_4^{\mathrm{B}} = y_2^{\mathrm{B}} \tag{28}$$

If industrial wastewater is selected ($y_4^{\mathrm{B}} = 1$), it can be transported either by the pressure sewage pipeline connection ($y_5^{\mathrm{B}} = 1$), or by cisterns ($y_6^{\mathrm{B}} = 1$):

$$y_5^{\mathrm{B}} + y_6^{\mathrm{B}} = y_4^{\mathrm{B}} \tag{29}$$

Finally, the following logical constraint manages the selection between wastewater treatment alternatives:

$$y_7^{\mathrm{B}} + y_8^{\mathrm{B}} = 1 \tag{30}$$

where the first alternative ($y_7^{\mathrm{B}} = 1$) represents a closed water system with the re-use of wastewater regenerated by ultrafiltation and reverse osmosis. This alternative is characterized by the side-production of an organic fertilizer. The second option ($y_8^{\mathrm{B}} = 1$) is an open water system with a central wastewater treatment unit.

## The objective function

The objective function maximizes the net present worth (NPW), in which investment cost is subtracted from discounted cash flows:

$$\max W_{\mathrm{NP}} = -I + \left[\frac{(1+r_{\mathrm{d}})^{t_{\mathrm{d}}} - 1}{r_{\mathrm{d}}(1+r_{\mathrm{d}})^{t_{\mathrm{d}}}}\right] \cdot F_{\mathrm{c}} \tag{31}$$

where $I$/(EUR), as defined by eq. (32) below, represents the investment needed for reconstruction, adaptation and building new processes, $r_{\mathrm{d}}$ a discount rate, $t_{\mathrm{d}}$/(a) the depreciation period, and $F_{\mathrm{c}}$/(EUR/a), as defined by eq. (33), denoting the cash-flow generated by the selected system.

### *Investment for the processes*

The investment $I$ for the processes is calculated by the following substitutive equation:

$$I = \sum_{j\in J_1} I_j^0 \cdot \left(\frac{q_{v_j}^{\mathrm{BG}}}{q_{v_j}^{\mathrm{BG},0}}\right)^n + \sum_{j\in J_2} I_j^{\mathrm{R},0} \cdot y_j^{\mathrm{P}} + \sum_{l\in L_1} I_l^{\mathrm{B}} \cdot y_l^{\mathrm{B}} \tag{32}$$

where $I_j^0$/(EUR) is the base capital investment of anaerobic conversion ($j \in J_1$), $q_{v_j}^{\mathrm{BG},0}$/(m$^3$ d$^{-1}$) the daily production of biogas for the base case biogas production in process $j$, $n$ denotes the investment exponent, $I_j^{\mathrm{R},0}$/(EUR) is the base capital investment for the rendering plant ($j \in J_2$), $I_l^{\mathrm{B}}$/(EUR) ($l \in L_1$) represents the capital investment for background alternatives, e.g. reconstruction of the pig farm ($y_1^{\mathrm{B}} = 1$) or adaptation of the existing pig farm for the production of poultry ($y_2^{\mathrm{B}} = 1$), the pressure sewage pipeline connection ($y_5^{\mathrm{B}} = 1$), and ultrafiltration and reverse osmosis ($y_7^{\mathrm{B}} = 1$).

## Cash flow

The cash flow is defined by the following substitutive equation:

$$F_c = (1 - r_t) \cdot (R - E) + r_t \cdot D \tag{33}$$

where $r_t$ represents the tax rate, $R$/(EUR/a) the revenues or incomes, $E$/(EUR/a) the expenditures for processes and $D$/(EUR/a) depreciation.

The term ($R - E$) represents the surplus of the incomes over the expenses. Incomes $R$ represent the revenue from selling electricity, heat, solid products, and organic fertilizer:

$$R = \left(\sum_{j\in J_1} (c^{\mathrm{ES}} \cdot q_{v_j}^{\mathrm{BG}} \cdot e_j^{\mathrm{BG}} \cdot \eta^{\mathrm{E}} + c^{\mathrm{TS}} \cdot q_{v_j}^{\mathrm{BG}} \cdot e_j^{\mathrm{BG}} \cdot \eta^{\mathrm{T}}) + \right. \\ \left. + \sum_{j\in J_2}\sum_{k\in K} c_k^{\mathrm{SP}} \cdot q_{m_{j,k}}^{\mathrm{SP}} + \sum_{j\in J_1}\sum_{l\in L_8} c_l^{\mathrm{OF}} \cdot q_{m_{j,l}}^{\mathrm{OF}} \right) \cdot f_d \tag{34}$$

where $c^{\mathrm{ES}}$ and $c^{\mathrm{TS}}$ both in EUR/(kW h) are the selling prices of the produced electricity and heat, respectively, $e_j^{\mathrm{BG}}$/((kW h) m$^{-3}$) is the heating value of biogas of processes $j$, $\eta^{\mathrm{E}}$ and $\eta^{\mathrm{T}}$ are the efficiencies of electricity and heat generation, respectively, $c_k^{\mathrm{SP}}$/(EUR/kg) is a price of solid product $k$ for the rendering plant, $c_l^{\mathrm{OF}}$/(EUR/kg) is the price of organic fertilizer from the wastewater treatment unit $l$, and $f_{\mathrm{d}}$/(d/a) is the number of annual operating days.

The expenses $E$ for the processes are further composed of costs for purchasing electricity and substrates, and costs for the treating and transportation of industrial wastewater:

$$E = \left(\sum_{j\in J_1} c^{\mathrm{E}} \cdot p_j^0 \cdot \frac{q_{v_j}^{\mathrm{BG}}}{q_{v_j}^{\mathrm{BG},0}} + \sum_{j\in J_1} c^{\mathrm{TS}} \cdot \phi_j^0 \cdot \frac{q_{v_j}^{\mathrm{BG}}}{q_{v_j}^{\mathrm{BG},0}} + \right. \\ + \left( c_f^{\mathrm{R},0} \cdot \sum_{j\in J_2} y_j^{\mathrm{P}} + c_v^{\mathrm{R},0} \cdot \frac{\sum_{i\in I_1}\sum_{j\in J_2} q_{m_{i,j}}}{\sum_{j\in J_2} q_{m_j}^{\mathrm{R},0}} \right) + \\ + c_i^{\mathrm{S}} \cdot \sum_{i\in I_6}\sum_{j\in J_1} q_{m_{i,j}} + c_l^{\mathrm{P}} \cdot \sum_{j\in J_1}\sum_{l\in L_9} q_{m_{j,l}}^{\mathrm{WW}} + \\ \left. + c_l^{\mathrm{T}} \cdot \sum_{i\in I_5}\sum_{l\in L_6} q_{m_{i,l}}^{\mathrm{T}} \right) \cdot f_d \tag{35}$$

where $c^{\mathrm{E}}$/(EUR/(kW h)) is the price of purchased electricity, which is, in general, different than the price of electricity produced from renewable resources, $p_j^0$/((kW h) d$^{-1}$) is the base-case electricity consumption of process $j$, the second term represents the heat consumption of process $j$, $\phi_j^0$/((kW h) d$^{-1}$) is the base-case heat consumption of process $j$, $c_f^{\mathrm{R},0}$, and $c_v^{\mathrm{R},0}$ are the base case fixed and variable operating cost coefficients for the rendering plant, $q_{m_j}^{\mathrm{R},0}$/(kg d$^{-1}$) is the base-case daily consumption of substrates in the rendering plant, while $c_i^{\mathrm{S}}$, $c_l^{\mathrm{P}}$, and $c_l^{\mathrm{T}}$ in (EUR/kg) are the cost coefficients for substrates (maize, freshwater), wastewater purification, and industrial wastewater transportation, respectively.

Finally, the depreciation is defined as a straight-line depreciation over a depreciation period, $t_D$/a:

$$D = \frac{I}{t_D} \tag{36}$$

Note that even if the aggregated MINLP model was developed for a specific industrial case study, it is data-independent in most of its parts and can, thus, be easily adapted and applied to similar example problems.

## Solution of the industrial case study

The last step of the superstructure approach is solving the MINLP problem, as applied to an existing large-scale meat company. Data for inlet waste material are given in Table 1, the model parameters

Table 1 – *Data for inlet waste material, other substrates and water supply*

| Waste material, other substrates and water supply, $i$ | $q_{m_{i,j}}^{\mathrm{LO}}$/kg d$^{-1}$ $j \in J_1$ | $q_{m_{i,j}}^{\mathrm{UP}}$/kg d$^{-1}$ $j \in J_1$ | $q_{m_{i,j}}^{\mathrm{UP}}$/kg d$^{-1}$ $j \in J_2$ | $q_{m_i}^{\mathrm{SU,P}} \cdot 10^3$/kg d$^{-1}$ | $w_i^{\mathrm{DMC}}$/% | $w_i^{\mathrm{VSS}}$/% | $S_i^{\mathrm{BG}}$/m$^3$ kg$^{-1}$ |
|---|---|---|---|---|---|---|---|
| 1 Liquid pig manure | 0.00 | 166.67 | 0.00 | 166.67 | 2 | 4.54 | 0.430 |
| 2 Pig manure | 0.00 | 13.89 | 0.00 | 13.89 | 5 | 18.56 | 0.400 |
| 3 Cattle manure | 0.00 | 50.00 | 0.00 | 50.00 | 8 | 6.4 | 0.320 |
| 4 Slaughterhouse wastes | 0.00 | 35.62 | 35.62 | 35.62 | 18 | 16.2 | 0.505 |
| 5 Animal offal | 0.00 | 10.83 | 10.83 | 10.83 | 18 | 16.2 | 0.505 |
| 6 Bones | 0.00 | 3.61 | 3.61 | 3.61 | 18 | 16.2 | 0.505 |
| 7 Slaughterhouse wastes | 0.00 | 3.44 | 3.44 | 3.44 | 18 | 16.2 | 0.505 |
| 8 Animal offal | 0.00 | 1.67 | 1.67 | 1.67 | 18 | 16.2 | 0.505 |
| 9 Bones | 0.00 | 0.22 | 0.22 | 0.22 | 18 | 16.2 | 0.505 |
| 10 Blood spills | 0.00 | 6.83 | 6.83 | 6.83 | 0.7 | 5.81 | 0.540 |
| 11 Agromerkur | 0.00 | 1.44 | 1.44 | 1.44 | 18 | 16.2 | 0.505 |
| 12 Poultry manure – new farm | 0.00 | 9.31 | 0.00 | 9.31 | 50 | 35 | 0.470 |
| 13 Industrial wastewater from poultry farm | 0.00 | 25.83 | 0.00 | 25.83 | 1 | 0.7 | 0.450 |
| 14 Industrial wastewater | 0.00 | 103.33 | 0.00 | 103.33 | 0.2 | 0.14 | 0.450 |
| 15 Industrial wastewater | 0.00 | 212.22 | 0.00 | 212.22 | 0.1 | 0.7 | 0.450 |
| 16 Freshwater | 0.00 | 972.22 | 0.00 | 972.22 | 0.00 | 0.00 | 0.000 |
| 17 Poultry manure broilers | 0.00 | 2.57 | 0.00 | 2.57 | 50 | 41 | 0.470 |
| 18 Poultry manure – layer | 0.00 | 6.60 | 0.00 | 6.60 | 60 | 42 | 0.450 |
| 19 Poultry manure – breeding | 0.00 | 2.19 | 0.00 | 2.19 | 80 | 56 | 0.350 |
| 20 Wheat straw | 0.00 | 11.36 | 0.00 | 11.36 | 85 | 76.5 | 0.200 |
| 21 Grape skins | 0.00 | 1.74 | 0.00 | 1.74 | 40 | 36 | 0.540 |
| 22 Hatchery waste | 0.00 | 1.11 | 0.00 | 1.11 | 30 | 27 | 0.760 |
| 23 Maize | 22.22 | 22.22 | 0.00 | 22.22 | 33 | 29.7 | 0.630 |
| 24 Flotate | 0.00 | 1.42 | 0.00 | 1.42 | 10 | 9.5 | 0.540 |
| 25 Flotate | 0.00 | 0.53 | 0.00 | 0.53 | 10 | 9.5 | 0.540 |

and biogas production data in Table 2, and economical data in Table 3. Inlet waste material data and data for other substrates have been collected and calculated as average values from actual annual reports in an existing large-scale meat company. Some other details (i.e. $w_i^{\mathrm{DMC}}/(\%)$, $w_i^{\mathrm{VSS}}/(\%)$, $S_i^{\mathrm{BG}}/(\mathrm{m^3\ kg^{-1}})$) have been taken from the internal project documentation of the meat company. Data for the model parameters as well data for the economical evaluation are taken from actual industrial case studies. All investment data for reconstructing the rendering plant, local farm, construction of a pressure sewage pipeline, and ultrafiltration and reverse osmosis, are estimated values. Also, average local market prices were used for product prices (i.e. meat meal, electric energy, etc), and for costs of wastewater treatment, maize, heat and electric energy etc. It should be noted that the biogas processes and rendering plant in the base-case design were heat integrated and that their cost coefficients and base-case data thus indirectly reflects heat integration in the aggregated MINLP model.

To our experience, the Branch and Reduce Optimization Navigator (BARON)[24] is the fastest and most robust global solver for solving the noncovex biogas synthesis model available in the modelling

T a b l e 2 – *Data for the model parameters and biogas production*

| | | |
|---|---|---|
| Model parameters | | |
| Base-case daily consumption of sub. for the rendering plant, kg d$^{-1}$ | $q_{m_j}^{\mathrm{R},0} = 52573$ | $j = 4$ |
| Base-case fixed operating cost coeffi. for the rend. plant, EUR d$^{-1}$ | $c_f^{\mathrm{R},0} = 3694$ | $j = 4$ |
| Base-case variable operating cost coeffi. for the rend. plant, EUR d$^{-1}$ | $c_v^{\mathrm{R},0} = 459$ | $j = 4$ |
| Mass fraction of the wastewater | $w^{\mathrm{WW}} = 0.9$ | |
| Split fraction of recirculated wastewater | $w_l^{\mathrm{RWW}} = 0.82$ | $l = 7$ |
| Dry matter content for the recirculated wastewater | $w_{j,l}^{\mathrm{DMC,RWW}} = 0$ | $l = 7$ |
| Mass fraction of solid products | $w_k^{\mathrm{SP}} = 0.25$ | $k = 1$ |
| | $w_k^{\mathrm{SP}} = 0.0937$ | $k = 2$ |
| | $w_k^{\mathrm{SP}} = 0.0293$ | $k = 3$ |
| Efficiency of electricity generation | $\eta^{\mathrm{E}} = 0.38$ | |
| Efficiency of heat generation | $\eta^{\mathrm{T}} = 0.45$ | |
| Biogas production | | |
| Biogas density, kg m$^{-3}$ | $\rho^{\mathrm{BG}} = 1.112$ | |
| Daily production of biogas for the base-case, m$^3$ d$^{-1}$ | $q_{m_j}^{\mathrm{BG},0} = 31762$ | $j = 1$ |
| | $q_{m_j}^{\mathrm{BG},0} = 17500$ | $j = 2$ |
| | $q_{m_j}^{\mathrm{BG},0} = 17500$ | $j = 3$ |
| Conversion factor of biogas production | $f_j = 2.34$ | $j = 1$ |
| | $f_j = 1.3$ | $j = 2$ |
| | $f_j = 1.3$ | $j = 3$ |
| Heating value of biogas production, (kW h) m$^{-3}$ | $e_j^{\mathrm{BG}} = 6.15$ | $j = 1$ |
| | $e_j^{\mathrm{BG}} = 5.80$ | $j = 2$ |
| | $e_j^{\mathrm{BG}} = 5.80$ | $j = 3$ |
| Base-case electricity consumed of process, (kW h) d$^{-1}$ | $p_j^0 = 12230$ | $j = 1$ |
| | $p_j^0 = 2500$ | $j = 2$ |
| | $p_j^0 = 2500$ | $j = 3$ |
| Base-case heat consumed of process, (kW h) d$^{-1}$ | $\phi_j^0 = 81184$ | $j = 1$ |
| | $\phi_j^0 = 16560$ | $j = 2$ |
| | $\phi_j^0 = 16560$ | $j = 3$ |

Table 3 – *Economical data*

| Economic data | | |
|---|---|---|
| Investment exponent | $n = 0.6$ | |
| Depreciation period, a | $t_D = 10$ | |
| Discount rate | $r_d = 0.1$ | |
| Tax rate | $r_t = 0.25$ | |
| Number of annual operating days, kg d$^{-1}$ | $d = 360$ | |
| Investment for background alternatives, EUR | $I_l^B = 5 \cdot 10^6$ | $l = 1$ |
| | $I_l^B = 2.5 \cdot 10^6$ | $l = 2$ |
| | $I_l^B = 1 \cdot 10^6$ | $l = 5$ |
| | $I_l^B = 1.8 \cdot 10^6$ | $l = 7$ |
| Investment of anaerobic conversion, EUR | $I_j^0 = 11.567 \cdot 10^6$ | $j = 1$ |
| | $I_j^0 = 11.985 \cdot 10^6$ | $j = 2$ |
| | $I_j^0 = 9.745 \cdot 10^6$ | $j = 3$ |
| Investment for the rendering plant, EUR | $I_j^{R,0} = 2 \cdot 10^6$ | $j = 4$ |
| Selling price of produced electricity, EUR (kW h)$^{-1}$ | $c^{ES} = 0.155$ | |
| Prices of surplus heat, EUR (kW h)$^{-1}$ | $c^{TS} = 0.05$ | |
| Selling price of solid product, EUR kg$^{-1}$ | $c_k^{SP} = 0.270$ | $k = 1$ |
| | $c_k^{SP} = 0.355$ | $k = 2$ |
| | $c_k^{SP} = 0.084$ | $k = 3$ |
| Price of organic fertilizer, EUR kg$^{-1}$ | $c_l^{OF} = 0.022$ | $l = 7$ |
| Cost coefficient of substrate, EUR kg$^{-1}$ | $c_i^S = 0.026$ | $i = 23$ |
| | $c_i^S = 0.0005$ | $i = 16$ |
| Price of the purchased electricity, EUR (kW h)$^{-1}$ | $c^E = 0.0833$ | |
| Cost coefficient of purification in wastewater treat. unit, EUR kg$^{-1}$ | $c_l^P = 0.0025$ | $l = 8$ |
| Cost coefficient of industrial wastewater transportation, EUR kg$^{-1}$ | $c_l^T = 0.004$ | $l = 4$ |
| | $c_l^T = 0.0$ | $l = 5$ |

system GAMS (General Algebraic Modeling System).[25] In theory, BARON will always find the global optimum if it is given sufficient time and if it is provided by finite lower and upper bounds on all nonlinear variables and expressions. The solver BARON combines constraint propagation, interval analysis, and duality with enhanced branch and bound algorithms in its search for globally optimal solutions under general assumptions.[26,27,28,29] Since the model is formulated in an aggregated, compact form, its size is reasonably small with only about 200 constrains, 170 continuous variables, and 12 binary variables. Combined with the efficient solver BARON, present-day personal computers, Intel (R) Celeron (R) M using a 1.50 GHz processor with 504 MB of RAM in our case, are capable of solving these sized problems in less than 1 s of CPU time.

The optimal solution is shown in Fig. 3. The economic analysis of the optimal, and some other solutions, for the case study of the meat company is shown in Table 4. From Fig. 3 it is evident, that the optimal solution is the thermophilic process for the utilization of the inlet substrates, which includes potential substrates from the new poultry farm and all slaughterhouse waste of category III. Also, the optimal scheme comprises a freshwater source from a local well, and an additional closed water system with technologies for the re-use of wastewater during the biogas production process. A by-product from wastewater treatment is an organic fertilizer, which can be sold. Note that the rendering plant was not selected. The net present worth (NPW) is 7.73 MEUR and the payback period 4.19 years. The disadvantage of the solution, as viewed regard-

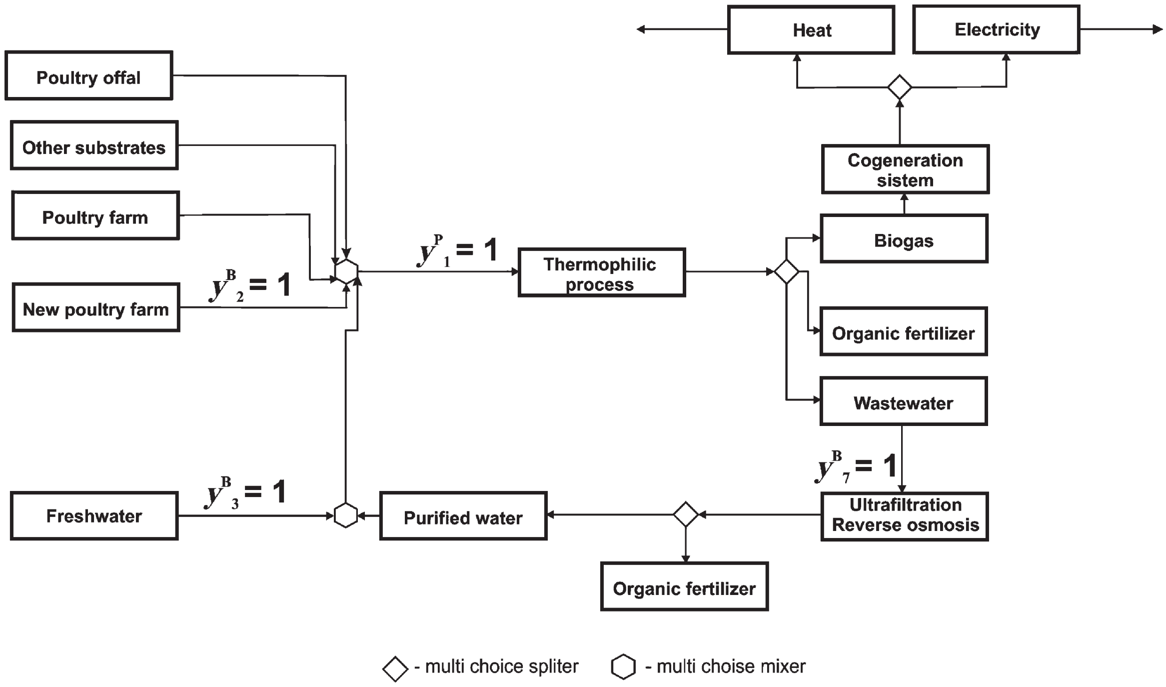
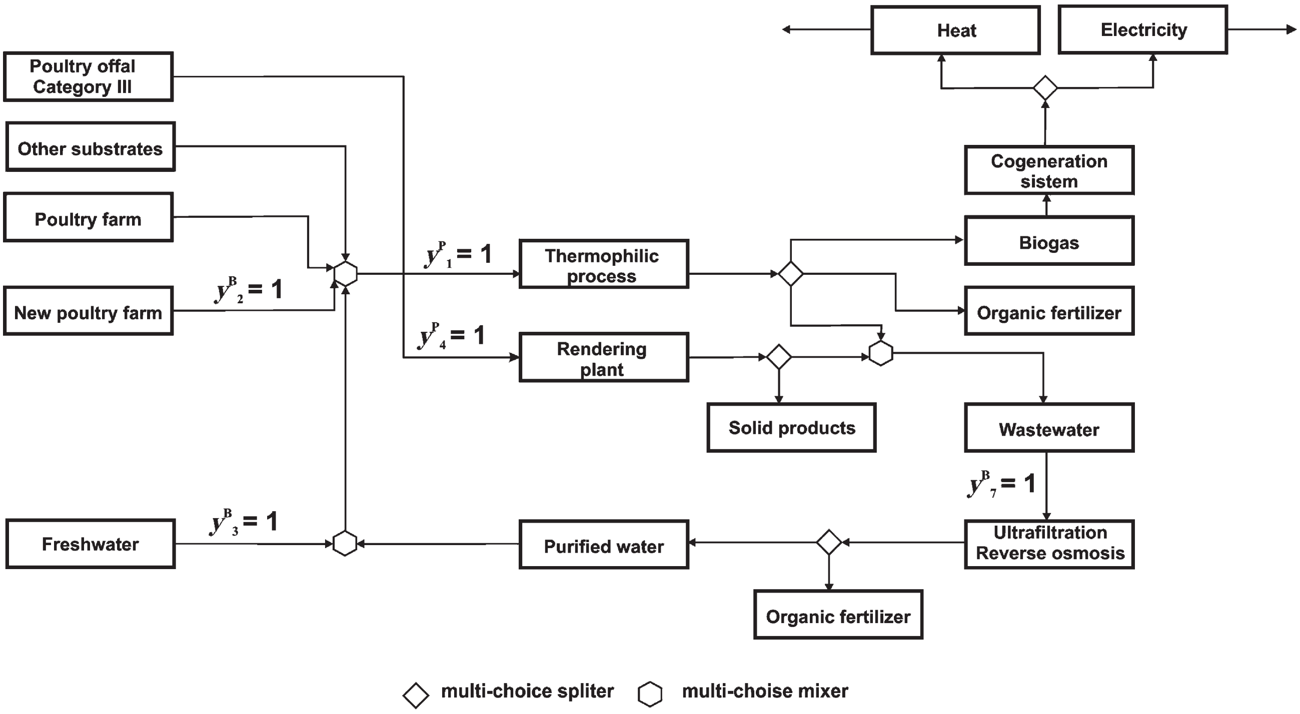



Fig. 3 – *Optimal solution for the industrial case study of biogas production in a thermophilic process without a rendering plant*

Table 4 – *Results for the industrial case study for biogas production without the rendering plant*

| Some process and economic quantities | Selected process | | | | |
|---|---|---|---|---|---|
| | – Thermophilic process<br>– New poultry farm<br>– Freshwater<br>– Closed system | – Thermophilic process<br>– Pig farm<br>– Closed system | – Thermophilic process<br>– New poultry farm<br>– Industrial wastewater<br>– Sewage pipeline<br>– Closed system | – Thermophilic process<br>– New poultry farm<br>– Industrial wastewater<br>– Cisterns<br>– Closed system | – Thermophilic process<br>– New poultry farm<br>– Freshwater<br>– Open system |
| $W_{NP}$/MEUR | **7.73** | 5.45 | 6.94 | 7.70 | 4.50 |
| $q_v^{BG}$/m$^3$ d$^{-1}$ | **35 587.2** | 35 457.4 | 35 687.5 | 35 687.5 | 35 587.2 |
| $q_m^{SP}$/t d$^{-1}$ | **0.00** | 0.00 | 0.00 | 0.00 | 0.00 |
| $q_v^{FW}$/m$^3$ d$^{-1}$ | **13.56** | 0.00 | 0.00 | 0.00 | 356.38 |
| $q_v^{OF}$/m$^3$ d$^{-1}$ | **75.25** | 72.69 | 75.28 | 75.28 | 0.00 |
| $I$/MEUR | **16.68** | 19.16 | 17.70 | 16.70 | 14.88 |
| $R$/MEUR a$^{-1}$ | **7.01** | 6.70 | 7.03 | 7.04 | 6.41 |
| $E$/MEUR a$^{-1}$ | **2.26** | 2.25 | 2.26 | 2.28 | 2.70 |
| $F_C$/MEUR a$^{-1}$ | **3.98** | 4.01 | 4.01 | 3.97 | 3.16 |
| $r_{IRR}$/% | **20.01** | 16.31 | 18.51 | 19.90 | 16.71 |
| $t_{PB}$/a | **4.19** | 4.78 | 4.41 | 4.21 | 4.71 |

$q_v^{FW}$/m$^3$ d$^{-1}$ = volume flow rate of freshwater,
$q_v^{OF}$/m$^3$ d$^{-1}$ = volume flow rate of an organic fertilizer,
$r_{IRR}$/% = internal rate of return and
$t_{PB}$/a = payback period




F i g . 4 – *Optimal solution for the industrial case study of biogas production in a combined thermophilic process, and a rendering plant*

ing sustainable development, is that the company would use freshwater from a local well, rather than wastewater from other meat processes. As expected, biogas production by anaerobic fermentation under thermophilic conditions has the highest yield of biogas production compared to the mesophilic process, irrespective of the quality and quantity of the inlet's organic and animal wastes. The optimal solution for anaerobic fermentation in combination with the rendering plant, is shown in Fig. 4. Based on economical analysis, if the rendering plant is selected, the optimal solution will never include the mesophilic process with a sterilization unit because of the additional investment for the sterilization unit. The best solution comprises the thermophilic unit, new substrates from the poultry farm with additional freshwater source, and a closed water network. The NPW is 4.91 MEUR and the payback period 4.72 years, see Table 5. From Tables 4 and 5, it is evident that biogas production increases when slaughterhouse wastes of category III are included during anaerobic fermentation, and that the NPW is significantly higher compared to the options using the rendering plant.

In the case, where the pig farm's reconstruction is selected, the results in Table 4 indicate that the NPW, the internal rate of return and the payback period decrease, since the investment increases. In accordance with long-term trends in the market, the options for a new poultry farm are more favourable than those for reconstructing the existing pig farm. The NPW and the internal rate of return are thus higher, and the payback period shorter.

From the economic point of view, the alternative structures that include the use of freshwater in combination of the re-use of wastewater in a closed water system, are the most favourable options. The transportation of industrial wastewater by the pipeline or by cisterns is unattractive. On the other hand, the pumping and transportation cost of the freshwater source are low and no additional investment is needed to supply water from the local well.

## Conclusion

An aggregated mathematical MINLP model was simultaneously developed for the selection of optimal biogas production alternatives from animal and other bio-waste together with the optimization of different process background alternatives. This model was applied to a large-scale industrial case study, in order to optimize the utilization of different organic and animal substrates in combination with various options for water supply, wastewater treatment in a closed or open water system, and the transportation of industrial wastewater. The results of economical analysis indicate that biogas production under thermophilic conditions without a rendering plant is the most attractive solution. In the

Table 5 – *Results for the industrial case study for the biogas production process in combination with the rendering plant*

| Some process and economic quantities | Selected process | | | | |
|---|---|---|---|---|---|
| | – Thermophilic process<br>– Rendering plant<br>– New poultry farm<br>– Freshwater<br>– Closed system | – Thermophilic process<br>– Rendering plant<br>– Pig farm<br>– Closed system | – Mesophilic process<br>– Rendering plant<br>– New poultry farm<br>– Freshwater<br>– Closed system | – Mesophilic process<br>– Rendering plant<br>– Pig farm<br>– Closed system | – Mesophilic process with sterilization unit<br>– New poultry farm<br>– Freshwater<br>– Closed system |
| $W_{\mathrm{NP}}$/MEUR | **4.91** | 3.30 | 0.10 | –1.77 | 2.78 |
| $q_v^{\mathrm{BG}}$/m$^3$ d$^{-1}$ | **24 204.6** | 25 557.3 | 13 446.9 | 14 198.5 | 19 770.7 |
| $q_m^{\mathrm{SP}}$/t d$^{-1}$ | **23.75** | 23.75 | 23.75 | 23.75 | 0.00 |
| $q_v^{\mathrm{FW}}$/m$^3$ d$^{-1}$ | **35.99** | 0.00 | 35.99 | 0.00 | 13.56 |
| $q_v^{\mathrm{OF}}$/m$^3$ d$^{-1}$ | **56.10** | 55.96 | 56.10 | 55.96 | 75.25 |
| $I$/MEUR | **16.13** | 18.95 | 14.62 | 19.37 | 14.79 |
| $R$/MEUR a$^{-1}$ | **7.17** | 7.42 | 4.87 | 5.22 | 3.96 |
| $E$/MEUR a$^{-1}$ | **3.14** | 3.209 | 0.006 | 2.04 | 0.63 |
| $F_C$/MEUR a$^{-1}$ | **3.42** | 3.62 | 2.66 | 2.86 | 2.86 |
| $r_{\mathrm{IRR}}$/% | **16.66** | 13.91 | 10.08 | / | 14.22 |
| $t_{\mathrm{PB}}$/a | **4.72** | 5.23 | 6.12 | / | 5.17 |

$q_v^{\mathrm{FW}}$/m$^3$ d$^{-1}$ = volume flow rate of freshwater,
$q_v^{\mathrm{OF}}$/m$^3$ d$^{-1}$ = volume flow rate of an organic fertilizer,
$r_{\mathrm{IRR}}$/% = internal rate of return and
$t_{\mathrm{PB}}$/a = payback period

case study, the net present worth by adapting the existing pig farm for the production of additional poultry is a 2.3 MEUR better option than for reconstructing the pig farm. At the moment, the use of freshwater in the process is economically more attractive since the cost of freshwater is relatively low compared to the additional investment for transporting industrial wastewater, either by a pressure sewage pipeline connection, or cisterns. However, due to rising freshwater prices and stricter environmental regulations, the use of industrial wastewater could become more advantageous. It should be noted that closed water circulation by ultrafiltration and reverse osmosis, significantly reduces the consumption of freshwater and, in addition, produces a noteworthy amount of valuable organic fertilizer. Some additional savings could also be obtained if simultaneous heat integration were preformed between process and process background alternatives. Therefore, the development of a more detailed model with simultaneous heat integration is under way. From the case study, it is evident that including process background alternatives in the optimization of a biogas process may significantly increase the benefits.

*ACKNOWLEDGMENT*

*The authors are grateful to the Slovenian Research Agency for its financial support (Program P2-0032, Project L2-0358, and PhD research fellowship contract No. 1000-06-310080).*

## Nomenclature

### Sets

$I$ – set of inlet substrates

$I_1$ – subset of slaughterhouse waste of III category, $I_1 \in I$

$I_2$ – subset of inlet substrates from the pig farm, $I_2 \in I$

$I_3$ – subset of potential inlet substrates from the new poultry farm, $I_3 \in I$

$I_4$ – subset of freshwater, $I_4 \in I$

$I_5$ – subset of industrial wastewater, $I_5 \in I$

$I_6$ – subset of substrates which can be purchased on the market, $I_6 \in I$

$K$ – set of solid products of the rendering plant

$J$ – set of production processes

$J_1$ – subset of anaerobic conversion processes, $J_1 \in J$

$J_2$ – subset of rendering plant, $J_2 \in J$

$J_3$ – subset of processes which can utilized the slaughterhouse waste of III category, $J_3 \in J$

$L$ – set of process background alternatives

$L_1$ – subset of processes, which need additional investment, $L_1 \in L$

$L_2$ – subset of an existing pig farm, $L_2 \in L$

$L_3$ – subset of a new poultry farm, $L_3 \in L$

$L_4$ – subset for the water supply as freshwater, $L_4 \in L$

$L_5$ – subset for the water supply as industrial wastewater, $L_5 \in L$

$L_6$ – subset for industrial wastewater transportation alternatives, $L_6 \in L$

$L_7$ – subset for wastewater treatment alternatives, $L_7 \in L$

$L_8$ – subset for a closed water system, $L_8 \in L$

$L_9$ – subset for an open water system, $L_9 \in L$

### Scalars and parameters

$c^{\mathrm{E}}$ – price of the purchased electricity, EUR/(kW h)

$c^{\mathrm{ES}}$ – selling prices of the produced electricity, EUR/(kW h)

$c_l^{\mathrm{OF}}$ – price of an organic fertilizer from the wastewater treatment unit $l$, EUR/kg

$c_l^{\mathrm{P}}$ – cost coefficient of wastewater purification $l$, EUR/kg

$c_f^{\mathrm{R},0}$ – base-case fixed operating cost coefficient for the rendering plant, EUR/d

$c_v^{\mathrm{R},0}$ – base-case variable operating cost coefficient for the rendering plant, EUR/d

$c_i^{\mathrm{S}}$ – cost-coefficient for substrate $i$, EUR/kg

$c_k^{\mathrm{SP}}$ – price of solid product $k$ for the rendering plant $j$, EUR/kg

$c_l^{\mathrm{T}}$ – cost-coefficient for industrial wastewater transportation $l$, EUR/kg

$c^{\mathrm{TS}}$ – price of surplus heat, EUR/(kW h)

$e_j^{\mathrm{BG}}$ – heating value of biogas of processes $j$, (kW h) m$^{-3}$

$f_d$ – number of annual operating days, d/a

$f_j$ – factor of biogas production for process $j$

$I_j^0$ – base capital investment of anaerobic process $j$, EUR

$I_l^{\mathrm{B}}$ – capital investment for background alternatives, e.g. the reconstruction of the pig farm ($y_1^{\mathrm{B}} = 1$) or adaptation of the existing pig farm for the production of poultry ($y_2^{\mathrm{B}} = 1$), the pressure sewage pipeline connection ($y_5^{\mathrm{B}} = 1$) and ultrafiltration and reverse osmosis ($y_7^{\mathrm{B}} = 1$), EUR

$I_j^{\mathrm{R},0}$ – base capital investment of rendering plant $j$, EUR

$n$ – investment exponent

$p_j^0$ – base-case electricity consumption of process $j$, (kW h) d$^{-1}$

$q_{m_{j,l}}^{\mathrm{OF,UP}}$ – upper bound for an organic fertilizer leaving process $j$, kg d$^{-1}$

$q_{m_j}^{\mathrm{R},0}$ – base-case daily consumption of substrates in the rendering plant $j$, kg d$^{-1}$

$q_{m_j}^{\mathrm{R,UP}}$ – upper bound of the residue for process $j$, kg d$^{-1}$

$q_{m_j}^{\mathrm{RWW,UP}}$ – upper bound of wastewater recirculated to process $j$, kg d$^{-1}$

$q_{m_i}^{\mathrm{S}}$ – mass flow-rate of available substrates $i$, kg d$^{-1}$

$q_{m_k}^{\mathrm{SP,UP}}$ – daily capacity of the rendering plant for the production of solid product $k$, kg d$^{-1}$

$q_{m_{j,l}}^{\mathrm{T,UP}}$ – upper bound for the wastewater, kg d$^{-1}$

$q_{m_{j,l}}^{\mathrm{WW,UP}}$ – upper bound of wastewater from process $j$ to alternative wastewater treatment unit $l$, kg d$^{-1}$

$q_{v_j}^{\mathrm{BG},0}$ – daily production of biogas for the base-case in process $j$, kg d$^{-1}$

$q_{v_j}^{\mathrm{BG,LO}}$ – lower bound on the production of biogas by process $j$, kg d$^{-1}$

$q_{v_j}^{\mathrm{BG,UP}}$ – upper bound on the production of biogas by process $j$, kg d$^{-1}$

$r_{\mathrm{d}}$ – discount rate

$r_{\mathrm{IRR}}$ – internal rate of return

$r_{\mathrm{t}}$ – tax rate

$S_i^{\mathrm{BG}}$ – specific biogas production from substrate $i$ per unit VSS under standard conditions, N m$^3$ kg$^{-1}$

$t_{\mathrm{D}}$ – depreciation period, a

$t_{\mathrm{PB}}$ – payback period, a

$w_i^{\mathrm{DMC}}$ – dry matter content of substrate $i$, –

$w_{j,l}^{\mathrm{DMC,RWW}}$ – dry matter content of the recirculated wastewater to process $j$, –

$w^{\mathrm{RDMC}}$ – required of dry matter content, –

$w_l^{\mathrm{RWW}}$ – split fraction of the recirculated wastewater, –

$w_k^{\mathrm{SP}}$ – mass fraction of solid product $k$ for the rendering plant, –

$w_i^{\mathrm{VSS}}$ – mass fraction of volatile suspended solid (VSS) in substrate $i$, –

$w^{\mathrm{WW}}$ – overall mass fraction of wastewater, –

$\eta^{\mathrm{E}}$ – efficiency of electricity generation

$\eta^{\mathrm{T}}$ – efficiency of heat generation

$\rho^{\mathrm{BG}}$ – density of the biogas, kg m$^{-3}$

$\phi_j^0$ – base-case heat consumption of process $j$, (kW h) d$^{-1}$

### Variables

$q_{m_{i,j}}$ – mass flow-rate of substrate $i$ in process $j$, kg d$^{-1}$

$q_{m_{i,j}}^{\mathrm{LO}}$ – lower bound of the required of mass flow-rates of substrates for processes $j$, kg d$^{-1}$

$q_{m_{i,j}}^{\mathrm{OF}}$ – mass flow-rate of an organic fertilizer leaving process $j$, kg d$^{-1}$

$q_{m_j}^{\mathrm{R}}$ – mass flow-rate of the residue leaving process $j$, kg d$^{-1}$

$q_{m_{j,l}}^{\mathrm{RWW}}$ – mass flow-rate of recirculated wastewater from the purification system $l$ to process $j$, kg d$^{-1}$

$q_{m_i}^{\mathrm{S}}$ – mass flow-rate of substrate $i$, kg a$^{-1}$

$q_{m_{j,k}}^{\mathrm{SP}}$ – mass flow-rate of solid product $k$ in process $j$, kg d$^{-1}$

$q^{\mathrm{T}}_{m_{j,l}}$ – mass flow-rate of transported industrial wastewater in process $j$, kg d$^{-1}$

$q^{\mathrm{UP}}_{m_{i,j}}$ – upper bound of available daily mass flow-rates of substrates for processes $j$, kg d$^{-1}$

$q^{\mathrm{WW}}_{m_{j,l}}$ – mass flow-rate of wastewater from process $j$ to wastewater treatment systems $l$, kg d$^{-1}$

$q^{\mathrm{WWC}}_{m_{j,l}}$ – mass flow-rate of wastewater from process $j$ in the closed water system $l$, kg d$^{-1}$

$q^{\mathrm{WWO}}_{m_{j,l}}$ – mass flow-rate of wastewater from process $j$ in the open water system $l$, kg d$^{-1}$

$q^{\mathrm{BG}}_{v_j}$ – volume flow-rate of biogas produced in process $j$, m$^3$ d$^{-1}$

$q^{\mathrm{FW}}_{v}$ – volume flow-rate of freshwater, m$^3$ d$^{-1}$

$q^{\mathrm{OF}}_{v}$ – volume flow-rate of an organic fertilizer, m$^3$ d$^{-1}$

$W_{\mathrm{NP}}$ – net present worth, EUR

## Substituted variables

$D$ – depreciation, EUR/a

$E$ – expenditures for processes, EUR/a

$F_{\mathrm{c}}$ – cash flow, EUR/a

$I$ – investment needed for reconstruction, adaptation and building a new process, EUR

$R$ – revenues or incomes, EUR/a

## Binary variables

$y^{\mathrm{B}}_{l}$ – binary variable for the selection of the corresponding background alternatives $l$

$y^{\mathrm{P}}_{j}$ – binary variable for the selection of optimal production process $j$

## References


1. *Narodoslawsky, M.,* Chem. Biochem. Eng. Q. **17** (2003) 55.
2. *Dovì, V. G., Friedler, F., Huisingh, D., Klemeš, J. J.,* J. Clean. Prod. **17** (2009) 889.
3. *Chynoweth, D. P., Owens, J. M., Legrand, R.,* Renew. Energ. **22** (2001) 1.
4. *Holm-Nielsen, J. B., Al Seadi, T., Oleskowicz-Popiel, P.,* Bioresource. Technol. doi:10.1016/j.biortech.2008.12.046.
5. IEA Bioenergy Task 37, Biogas Production and Utilisation, Aadorf, Switzerland, 2005.
6. *Steffen, R., Szolar, O., Braun, R.,* Feedstocks for anaerobic Digestion, Vienna, Austria, 1998.
7. *Weiland, P.,* Appl. Biochem. Biotech. **109** (2003) 263.
8. *Mata-Alvarez, J., Macé, S., Llabrés, P.,* Bioresource. Technol. **74** (2000) 3.
9. *Salminen, E., Rintala, J.,* Bioresource. Technol. **83** (2002) 13.
10. *Ward, A. J., Hobbs, P. J., Holliman, P. J., Jones, D. L.,* Bioresource. Technol. **99** (2008) 7928.
11. *Kiyohara, Y., Miyahara, T., Mizuno, O., Noike, T., Ono, K.,* J. Chart. Inst. Water. E. **14** (2000) 150.
12. *Chae, K. J., Jang, A., Yim, S. K., Kim, In, S.,* Bioresource. Technol. **99** (2008) 1.
13. *Zábraská, J., Štêpová, J., Wachtl, R., Jeníček, P., Dohányos, M.,* Water. Sci. Technol. **42** (2000) 49.
14. *Voća, N., Krička, T., Ćosić, T., Rupić, V., Jukić, Ž., Kalambura, S.,* Plant Soil Environ. **51** (2005) 262.
15. *Chen, Y., Cheng, J. J., Creamer, K. S.,* Bioresource. Technol. **99** (2008) 4044.
16. *Llaneza Coalla, H., Blanco Fermández, J. M., Morís Morán, M. A., López Bobo, M. R.,* Bioresource. Technol. **100** (2009) 3843.
17. *Singh, P. P., Ghuman, B. S., Grewal, N. S.,* Energy. Convers. Manage. **39** (1998) 51.
18. *Biswas, J., Chowdhury, R., Bhattacharya, P.,* Biomass. Bioenerg. **31** (2007) 80.
19. *Lübken, M., Wichern, M., Schlattmann, M., Gronauer, A.,* Water. Res. **41** (2007) 4085.
20. *Gielen, D., Fujino, J., Hashimoto, S., Moriguchi, Y.,* Biomass. Bioenerg. **25** (2003) 177.
21. *Grossmann, I. E., Kravanja, Z.,* Mixed-Integer Nonlinear Programming: A Survey of Algorithms and Applications, *Biegler, L. T., Coleman, T. F., Conn, A. R., Santosa, F. N.* (Eds.), Large-Scale Optimization with Applications, Springer-Verlag, New York 93, 1997, pp 73-100.
22. *Biegler, L. T., Grossmann, I. E.,* Comput. Chem. Eng. **28** (2004) 1169.
23. *Grossmann, I. E., Biegler, L. T.,* Comput. Chem. Eng. **28** (2004) 1193.
24. http://www.gams.com/dd/docs/solvers/baron.pdf
25. *Brooke, A., Kendrick, D., Meeraus, A., Raman, R.,* GAMS: A Users Guide, The Scientific Press, Washington, 2005.
26. *Ryoo, H. S., Sahinidis, N. V.,* Comput. Chem. Eng. **19** (1995) 551.
27. *Nikolaos, V., Sahinidis, N. V.,* BARON Branch And Reduce Optimization Navigator, User's Manual: Version 4.0, (2000), http://archimedes.cheme.cmu.edu/baron/manuse.pdf
28. *Tawarmalani, M., Sahinidis, N. V.,* Math. Program. **99** (2004) 563.
29. *Sahinidis, N. V., Tawarmalani, M.,* J. Global. Optim. **32** (2005) 259.