CHEMICAL ENGINEERING TRANSACTIONS

VOL. 81, 2020

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081125

Resolving Discrepancies in Reported Flow Amounts in Sewage Sludge Management Network Datasets by Mathematical Programming

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For further development and infrastructure planning, considerations regarding economically feasible, efficient and appropriate waste management are essential. In current waste management networks and related datasets, errors and discrepancies arise in the reported values, to due to an insufficient detail of used infrastructure, which is often reduced to only several nodes in the case of very complex tasks. This paper presents an optimised multi-criteria mathematical programming model, which enables to obtain data for more detailed infrastructure while preserving the efficiency of the calculation using mathematical modifications and algorithms. The paper describes the method of how to divide the estimated flows in a chosen area among different sources. The optimized robust model minimizes the total sum of absolute deviations from the original data. It also considers logistics in the form of distances and emulates the economic behaviour of subjects in the network. The alternating direction method of multipliers is applied for an original model solution, together with a heuristic used for one set of ambiguous variables. This algorithm facilitates the solving of large instances of the defined problem. The implementation of the algorithm and all computations are done in the Julia programming language involving specialized optimisation libraries. The functionality of the optimised model is shown on the sewage sludge management network dataset of the Czech Republic, which contains approximately 200 entities. Such a dataset leads to the model with approximately 400,000 of decision variables. The results of the presented case study are used for the improvement of the treatment of sludge, a waste produced in wastewater treatment plants. The proposed model is general enough as it can be also used for estimating real waste flow datasets containing a similar type of error as described.

1. Introduction

Current research in waste management deals with several challenges. The aim is to ensure economically and ecologically efficient and in the long-term sustainable waste management concept. Material flow analysis (MFA) is a common approach used in strategic planning in the waste management area (Millette et al., 2019). Using this approach, current studies usually provide only a limited insight into the issue, due to an insufficient detail of used infrastructure, which is often reduced to only several nodes in the case of very complex tasks (Trochu et al., 2018). In such a way obtained, aggregated results do not provide the information detailed enough to support local planning. Considering the computational complexity, only limited possibilities are available to calculate such complex tasks in greater detail, as with more detailed territorial division, the number of variables in the model increases rapidly. In a combination with integer or nonlinear dependencies, which reflect real relations, it is a computationally demanding problem, which is often optimised in a reasonable time only locally or for an acceptable relative or absolute error (Mohammadi et al., 2019). In the previous work (Šomplák et al., 2019), the authors suggested a methodology allowing the calculation at a regional level of 14 nodes, corresponding to 14 Czech provinces. The presented article aims to extend this concept of optimisation to a more detailed infrastructure (approx. 200 micro-regions) while preserving the efficiency of the calculation using mathematical

Paper Received: 25/05/2020; Revised: 01/06/2020; Accepted: 04/06/2020
Please cite this article as: Václavková Š., Pluskal J., Šomplák R., Talpa J., Smejkalová V., 2020, Resolving Discrepancies in Reported Flow Amounts in Sewage Sludge Management Network Datasets by Mathematical Programming, Chemical Engineering Transactions, 81, 745-750 DOI:10.3303/CET2081125

modifications and algorithms. The use of the introduced mathematical model is demonstrated on the reconstruction of sewage sludge management network, showing that this approach can provide more accurate results, and enables for the implementation of an efficient processing chain with the link to the phosphorus (P) management.

Sewage sludge is a P-rich waste originating in the wastewater treatment plants (WWTP). The simplified balance of flows at WWTP with marked P-related flows is shown in Figure 1. As it is one of the most concentrated P waste flows (van Dijk et al., 2016), its importance arose lately (Mangwandi et al., 2011) in connection with concerns regarding food safety (Egle et al., 2016). Sewage sludge direct agricultural application has been the most common way of waste P utilization, where stabilized sludge typically contains 15-40 g of P per kg of its dry matter (Václavková et al., 2018). In this way, not only P but also significant portions of other nutrients, nitrogen (Santinelli et al., 2013) and organic carbon are given back to the agriculture (Zoboli et al., 2016). The presence of contaminants including pathogenic microorganisms, potentially toxic metals (Václavková et al., 2018) and residues of drugs or daily care products (Harrison et al., 2006) significantly reduces the suitability of such was of P utilization, end employment of alternative and economically feasible technologies is required in sludge-P management. It was shown that for efficient waste management design and planning, the information on the composition and treatment is not sufficient (Zheng, 2017) and it is necessary to understand the flow amounts of waste (sludge) from producer to its current as well as to its future processor.

In the first step, the current sludge management flows are analysed, as suggested by Zheng et al. (2017). Some information regarding sludge producers is being lost in the current system due to the errors in existing databases and due to the aggregation of streams and sludge handling types (management) among individual entities (Šomplák et al., 2017). The data aggregation occurs as a consequence of the sludge reporting administrative system, where amounts of waste produced, processed, utilized or removed are often presented by aggregated territorial administrative units (the whole country). In reality, there may be more than one sludge management entity within the same territorial administrative unit, as described in detail by Šomplák et al. (2017). Šomplák et al. (2019) presented a mathematical model, which allows estimating the distribution of waste flows and types of handling for the more detailed territorial division. The model was verified by a case study on bulky waste management in the Czech Republic (CZ), where the whole country (about 10 M inhabitants) was divided into territorial regions of about 700,000 inhabitants, corresponding to 14 country provinces (i.e. administration units of the 2nd level of the county territorial division system). In the current case study, the model is modified, allowing to describe and estimate the distribution of waste flows and handling types for even smaller territorial units, such as micro-regions (3rd level of the territorial division system, often including several individual municipalities). The smaller data aggregation allows for more accurate task results, as fewer waste streams flow runoffs occur in the task. However, such a model modification raises the number of model variables to dozens of millions of cases, being a challenge for the scientific model solution. Obtaining a more detailed description of sludge flows and handling types is crucial for effective system change planning, in the case of sludge, the utilization at the place of origin with a consequent return of P into the agriculture is preferred.

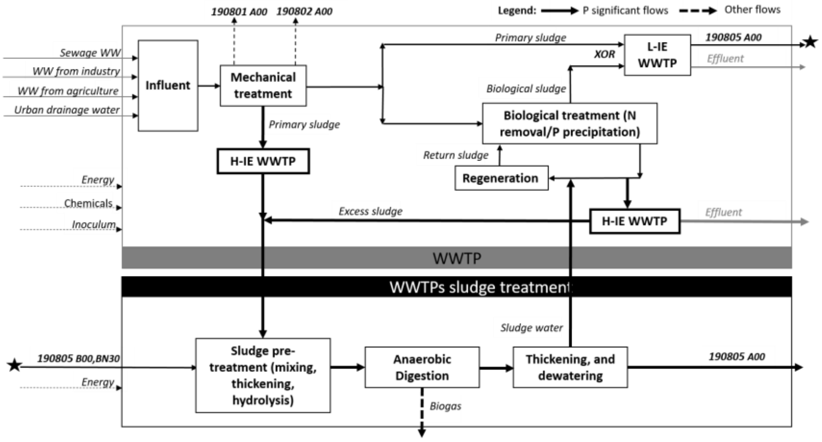

Figure 1: WWTP - Simplified balance of flows at WWTP marking P-related flows; L-EO WWTP represents smaller WWTPs with lower inhabitants equivalent (IE) capacities, H-EO represents higher WWTPs with bigger inhabitants equivalent (IE) capacities and codes 190801, 190802 and 190805 refers to a type of waste according to the European Waste Catalogue (EWC, 2014)

2. Methods

Sludge is a byproduct of the WWTP, where WWTPs with higher capacity typically operate so-called sludge management, where the sludge is stabilized and dewatered (Figure 1). The proportion and quality of each input significantly influence the composition of outputs and also the expected sludge P-content. It is necessary to include this aspect in the complex network flow task solution, which is the object of our further research.

2.1 The model modification

The used mathematical model is based on Šomplák et al. (2019), but here it is advisable to explain the issue of local cycles in the system nodes. Despite the more detailed territorial division applied, the data are still presented in aggregated form, where nodes represent larger territorial units or aggregately reported data for multiple entities from the same municipality. This is given by the situation, where a waste (sludge) is transported between entities but within the one considered territorial unit. In this aggregated form, the subjects are merged into one node. Such a situation is modelled as a loop, i.e. the edge begins and ends in the same node, see Figure 2. To correctly describe the problem, such a loop alone is not enough. The produced or imported waste in the given node may be handled by one of the following three options:

- local waste transfer within the node $x_{i,i}$,
- direct shipped quantity x_i^{dir},
- treatment at a given node t_i^{dir}.

This approach creates a "mini-network" for each aggregated node in the model, which is captured by constraints Eq(1), Eq(2) and Eq(3). The balances of the individual "nodes" of this "mini-network" are shown in Figure 2.

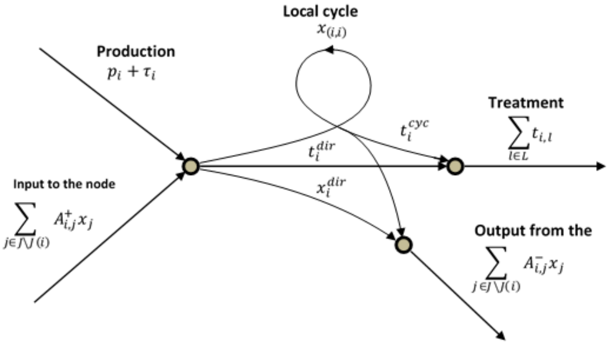

Figure 2: Schematic representation of the local cycle

A mathematical model describing the flow of sludge from producer to the point of further treatment is based on the network flow modelling principle.

Sets

$i \in I$	node, the whole element in Figure 2	$l \in L$	treatment node
$o \in I$	Producer	$j \in J$	arc

Parameters

p_i	waste production in the node i	$x_{j,o}$	waste transportation within arc j from producer o
τ_i	waste production error in the node i	$x_{i,o}^{dir}$	exported waste from i, producer o
$\delta_{i,o}$	binary parameter, $\delta_{i,o} = 1$ if $i = o$, otherwise 0	$t_{i,o}^{dir}$	direct waste treatment (without loop) in the node i from producer o
$t_{i,l}$	waste treatment	$t_{i,o}^{cyc}$	waste treatment in the node i from producer o after the loop
$A_{i,j}^{+}$	incidence matrix for imported waste	$A_{i,j}^{-}$	incidence matrix for exported waste

Constraints

$$\delta_{i,o}(p_i + \tau_i) + \sum_{j \in J \setminus J(i)} A_{i,j}^{+} x_{j,o} = x_{i,o}^{dir} + t_{i,o}^{dir} + \sum_{j \in J(i)} x_{j,o} \qquad \forall i, o \in I, \qquad (1)$$

$$x_{i,o}^{dir} + \sum_{j\in J(i)} x_{j,o} - t_{i,o}^{cyc} = \sum_{j\in J\setminus J(i)} A_{i,j}^{-} x_{j,o} \qquad \forall i,o \in I, \qquad (2)$$

$$\sum_{l\in L} t_{i,l} = \sum_{o\in I} (t_{i,o}^{cyc} + t_{i,o}^{dir}) \qquad \forall i \in I. \qquad (3)$$

A suitable modification of the above-mentioned mathematical model (Šomplák et al., 2019) is based on a modification of the task, using the iterative approach called the Alternating Direction Method of Multipliers (ADMM), see Boyd (2011). For the modified model, it is necessary to adjust the above-introduced model into the general form Eq(4).

$$\begin{aligned} &\min f(y) + g(x) \\ &\text{s.t. } Ax = y. \end{aligned} \qquad (4)$$

Since all equality constraints of the modified model are linear, the model is already in the desired general form $Ax = b$, where x represents the vector of all variables in the model, A is the matrix of the coefficients of these variables and b is the right side vector of the constraints. Constraints in the form of inequalities are moved to the objective function in the form of an indicator function:

$$I_{\{\geq b\}}(x) = \begin{cases} 0; & x \geq b, \\ \infty; & \text{otherwise.} \end{cases} \qquad (5)$$

Such indicator functions together with one of the original objective functions then represent the expression $g(x)$ in Eq(4). The function $f(y)$ is simply introduced as an indicator function of equality $y = b$.

3. Case study

The model described in section 2 was used to analyse data on the production and handling of sludge within the CZ networks on the level down to micro-regions. There are about 200 micro-regions (nodes) in CZ, consisting of more than 6,200 individual municipalities. For the model purposes, sludge is a P-rich waste originating at WWTPs, which is listed under the code number 19 08 05 by EWC. The network contains 227 nodes and 1,070 arcs excluding arcs with the zero-waste flow. Energy recovery, material recovery, disposal, pre-treatment, and others are considered as sludge treatment methods. If aggregated values for whole provinces are given in this section, it is done to improve data readability.

The differences between the amount of sludge produced and processed in the individual country provinces are shown in Figure 3. These values represent the input data for the model. The obvious fail to the mass balance shows the necessity of the sludge transport between provinces. For example, in the capital city, Prague, a big amount of sludge is produced, but none is utilized, as there is no agriculture in this urban area, and it must be transported to other regions such as neighbouring Central Bohemian province. The results of the calculation including information about the individual producers and the type of follow-up sludge handling are shown and discussed in section 3.1.

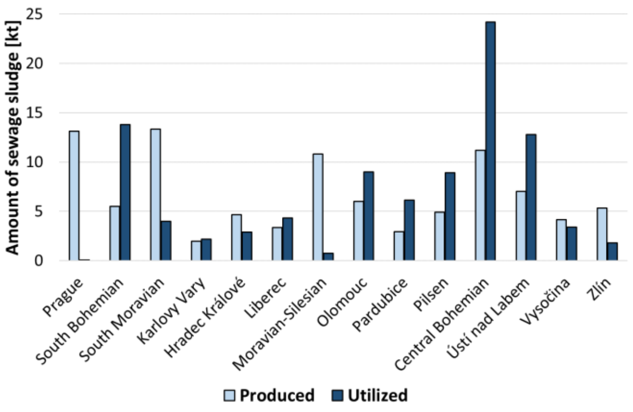

Figure 3: Sludge production and utilization in the 14 Czech provinces (Ministry of the environment of the Czech Republic, 2015)

3.1 Individual provinces

The relative share of sludge utilization types (results of the network flow model) aggregated for 14 individual Czech provinces is shown in Figure 4. The average treatment method for the whole country is depicted too. In most cases, material recovery is the predominant type of sludge utilization. That means mainly a direct agricultural application of stabilized sludge, which in practice means a return of P into the agriculture and soil. The relative share of sludge utilization types as a result of our more detailed approach is shown in chapter 3.2.

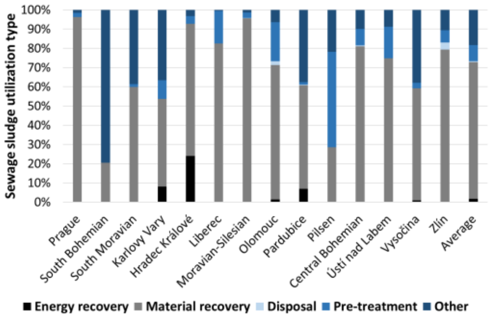

Figure 4: The relative share of sludge utilization types in the 14 Czech provinces

3.2 Selected micro-region

The main contribution of this approach is in the ability to use more detailed infrastructure than provinces to achieve more accurate results and its application afterwards. The main model asset is its ability to deal with data that are more detailed and obtain more accurate results for smaller administration units than provinces. An example of detailed model results on the level of a micro-region is shown on the map in Figure 5 (micro-region Havlíčkův Brod, HB, in Vysočina province). The map shows the import of the sludge within the province from micro-region Pelhřimov to HB, but also, that the sludge export to other micro-regions and provinces, mainly for material recovery purposes, with an exception in micro-region Hořovice in Central Bohemian province, where sludge is pre-treated. Presented results confirm the high share of material recovery among sludge handling types, where material recovery enables for sludge nutrients utilization in agriculture. However, this is limited in highly urbanized regions, where alternative handling must be employed.

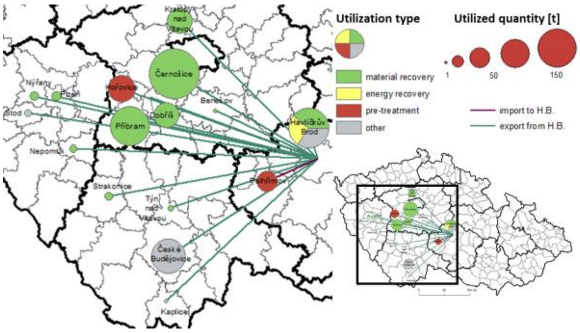

Figure 5: Sludge utilization type and flow for a selected micro-region called Havlíčkův Brod

By this approach, each of the 227 considered micro-regions in CZ will be analysed. These estimates of sludge handling type and treated amount in each micro-region could help to identify the potential for improvement of the sludge management system and allow for more efficient planning of P utilisation. That will include, shortly, employment of newly developed technologies, which would allow for P recovery. To design an economically feasible system for the given region, a more detailed analysis of links between WWTP and sludge composition is additionally needed.

4. Conclusion

The paper presented the specific part of a complex approach, which is focused on modelling sludge flow using data available in CZ. It also represents a fundamental building block for our next research. Used model modification is based on an already existing approach for the modelling of current flows and waste utilization types using the ADMM method. The problem of data aggregation in nodes was introduced in greater detail, which was solved by virtual cycles. The presented approach helps to analyse the current state of sludge management in the detail of micro-regions. The approach was shown on the example of sludge management in the CZ. Future research will be focused on dealing with the sludge handling in greater detail to the fate of sludge P content. The ability of future sludge P utilization is depended on the inputs into the WWTP, the type of wastewater treatment and sludge handling employed within the WWTP which influences the form of P in sludge. Considering the P content of produced sludge reaching up to 40 g/kg sludge dry matter and its form, it is possible to propose future changes in the treatment structure system with a focus on individual producers and the creation of new sludge treatment infrastructure.

Acknowledgements

The authors gratefully acknowledge the financial support provided by ERDF within the research project No. CZ.02.1.01/0.0/0.0/16_026/0008413 "Strategic Partnership for Environmental Technologies and Energy Production".

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