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Implementation of OPTIMASS to optimise municipal wastewater sludge processing chains: Proof of concept

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ABSTRACT

In sludge management, sludge is increasingly perceived as a marketable product rather than as a waste material. This awareness in combination with the variety of factors influencing the optimal management strategy and disposal route, introduces the need to optimise the sludge treatment throughout the whole chain instead of only minimising its production. In this paper, OPTIMASS, a mixed integer linear programming model to optimise strategic and tactical decisions in biomass-based supply chains, is proposed in order to meet this need. The applicability of OPTIMASS is illustrated through its implementation with a view to minimise the overall global warming impact of a real municipal wastewater sludge processing chain in "region X". A first scenario addresses the optimisation of the allocation and treatment of municipal wastewater sludge within the current network. Second, OPTIMASS is used to identify the optimal location(s) for new drying facilities in this chain. Finally, the effect on the optimal chain of changes in municipal wastewater sludge production and of changes in global warming impact of the cement industry as a disposal route is evaluated.

The analysis reveals that municipal wastewater sludge processing chains can be considered to be instances of the generic biomass-based supply chain and that the OPTIMASS tool can be applied to support strategic and tactical decisions for optimising sludge management in case new technologies, new treatment facility locations, new disposal options, etc. are at stake. The validity of the OPTIMASS approach is confirmed by the close correspondence between its outcome and the results of a decision support system, specifically developed for the municipal wastewater sludge processing chain.

1. Introduction

Incineration and landfilling have been and still are among the most frequently applied sludge disposal practices (Hospido et al., 2005). The contrast between the increasing world's sludge production and the decreasing disposal outlets in combination with the increasingly stringent environmental quality requirements for sludge disposal, induces a rising interest in alternative and beneficial uses of sludge (Samolada and Zabaniotou, 2014; European Commission, 2001). Promising strategies encompass application of sludge as compost (Song and Lee, 2010; Ribeiro et al., 2010) and for energy recovery through anaerobic digestion (Razaviarani et al., 2013; Astrup et al., 2014; Chawla et al., 2014) or thermal methods such as incineration, gasification and pyrolysis (Evangelisti et al., 2014; Vandenbo et al., 2014). Worldwide, the transformation of sludge into industrial fuel, such as fuel briquettes or pellets to be used in among others the cement industry is gaining interest (Solisio and Dovi, 2013; Hara and Mino, 2008; European Commission, 2001; Vandenbo et al., 2014).

Removal of moisture by thickening, dewatering and/or drying treatments can reduce the overall mass (weight) of the sludge up to 99% which makes transport more practical and less costly in comparison to the transport of untreated sludge (Mitchell and Beasley, 2011). However, transport of untreated sludge will always be required because treatment operations are only economically justifiable at larger wastewater treatment plants (WWTP) (Mitchell and Beasley, 2011). The multitude of transports of untreated and treated sludge in combination with the disposal of the residual sludge is not only a major expense, but also a burden for the

Abbreviations: DM, dry matter; GWImpact, global warming impact; LCI, life cycle inventory; MILP, mixed integer linear programming; WWTP, wastewater treatment plant.

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environment. In this context, life cycle assessment (LCA) has been applied to verify and analyse environmental issues in the decision-making process aiming at more sustainable sludge management (Hospido et al., 2005; Yoshida et al., 2013; Astrup et al., 2014; Bernard et al., 2014; Mills et al., 2014). Nevertheless, a variety of factors and perceptions influences the definition of the optimal sludge management strategy and the best disposal route (Cartmell et al., 2001). For example, physical and chemical properties of sludge will vary within the specific wastewater processing chain (Cartmell et al., 2001).

Most commonly, sludge is perceived as a waste material whereby the processing chain is configured to minimise sludge production (Cartmell et al., 2001). The recent perception shift to sludge as a resource and so as a marketable product induces a change to optimise sludge production and processing considering the whole chain (Cartmell et al., 2001). This view creates the need for a decision environment to define the optimal combinations of treatments and disposal routes among the different alternatives (Halog and Bortsie-Aryee, 2013) to ensure that the right goods are conveyed safely to the correct place at the right time at the lowest possible cost (Cartmell et al., 2001). Already in 1988, Larson developed a model used by the city of New York to design a new logistics system to transport municipal sewage sludge from city-operated wastewater treatment plants to a new ocean dumping site 106 mi offshore. The model provides an integrative framework for strategic planning considering fleet sizing, choice of vessel size, sizing local inventory holding capacities, and analysing system behaviour with and without transhipment (Larson, 1988). Mitchell and Beasley (2011) describe a linear programming model to optimise the sludge treatment and transport implemented within the UK regional water company, Yorkshire Water. However, the decision problem only relates to the flows since no variables are directly associated with treatment (Mitchell and Beasley, 2011). Olajire and Shah (2009) present a multi-period linear programming model to optimise the inventory management of sludge from wastewater treatment to disposal through a network including export, transfer and final treatment facilities. The objective is to minimise the total costs over all planning time periods (Olajire and Shah, 2009). Vandenbo et al. (2014) optimise the regional sewage sludge management with multiple environmental objectives. Solisio and Dovi (2013) go beyond the determination of the shortest path between sources and facilities by considering the supply chain as a three party-game between sludge makers, sludge movers and sludge takers. Each participant optimises his own activity with the sole limitation of finding a party who accepts his conditions for volumes and prices (Solisio and Dovi, 2013). The Pareto efficient situation defines the set of conditions accepted by all stakeholders (Solisio and Dovi, 2013). Eksioglu et al. (2011) and Marufuzzaman et al. (2014) present models to design and evaluate the performance of the supply chain for respectively biocrude and biodiesel production using sludge from wastewater treatment facilities as one of the biomass sources. Recently, Görgüner et al. (2015) have introduced transport cost-based optimisation model to determine the lands that would be receiving sludge in a pre-defined management period.

To the best of our knowledge, the optimisation models mentioned above are the only models described in literature to optimise the sludge processing chain. Probably, many more case specific models have been developed without being published. Although treatment of sludge is one of the decisive factors in the optimisation process, these models mainly focus on the optimisation of the transport without considering changes in characteristics of sludge along the processing chain (Cartmell et al., 2001). This problem corresponds to the problem addressed in De Meyer et al. (2015b) in which a mixed integer linear programming (MILP), OPTIMASS, has been introduced to optimise strategic and tactical decisions in all kinds of biomass supply chains considering among others changes in biomass characteristics due to handling operations. Motivated by the similarities between the biomass supply chain and the sludge processing chain, this paper investigates the possibility to implement OPTIMASS to optimise the sludge processing chain considering the changes in sludge characteristics due to the treatments. As an illustrative example, OPTIMASS has been applied to minimise the global warming impact (GWImpact) of the municipal wastewater sludge processing chain in "region X" (Section 2). Two theoretical scenarios have been addressed: (1) definition of the optimal allocation and treatment of municipal wastewater sludge within the current network, and (2) theoretical definition of the optimal location of new drying facilities in this chain (Section 3). A sensitivity analysis gives insight in the influence of changes in municipal wastewater sludge production and the effect of changes in the GWImpact of the disposal routes (more specifically the cement industry) on the optimal allocation and treatment of municipal wastewater sludge within the current network (Section 4). First, these analyses are meant to evaluate the applicability of OPTIMASS to optimise different kinds of strategic and tactical planning problems in a sludge supply chain. The second objective of this paper is to show genericity of OPTIMASS for its implementation in different types of biomass-based supply chains considering different circumstances and addressing different planning problems. Third, this paper aims to validate OPTIMASS by comparison of the results with the outcome of a decision support system specifically developed for the municipal wastewater sludge processing chain studied in this paper (Section 5). Finally, the results are summarised and analysed to define of opportunities for future research and development (Section 6).

2. Methods and materials

2.1. OPTIMASS

The mixed integer linear programming (MILP) model, OPTIMASS, is designed to support strategic and tactical decisions in all kinds of upstream biomass-based supply chains aiming at maximal net energy output, maximal revenue or minimal global warming potential (De Meyer et al., 2015b). This implies that OPTIMASS defines the optimal location, technology and capacity of operations and operation facilities simultaneously with the optimal allocation of raw biomass materials, intermediate products and by-products from the biomass production site to operation facilities and between operation facilities (De Meyer et al., 2015b). Different from existing optimisation models is that OPTIMASS considers changes in biomass characteristics due to handling operations and the re-injection of by-products from the conversion process in the supply chain (De Meyer et al., 2015b). OPTIMASS is based on a generic cradle-to-gate analysis of the biomass supply chain distinguishing six key operations from the point of harvesting raw materials to the delivery of the products to the conversion facility: i.e. biomass production, harvest, collection, pre-treatment, storage and conversion to bioenergy (Fig. 1) (De Meyer et al., 2015b). OPTIMASS is not intended to optimise the conversion process itself, but considers the conversion operations as a black box with input of biomass and output of bioenergy and by-products (De Meyer et al., 2015b). The MILP model incorporates constraints to regulate the sequence of operations, to ensure the mass balance in the flow of products through operations, between operations and between locations and to guarantee the meeting of a pre-defined energy and/or by-product demand (De Meyer et al., 2015b).

To test OPTIMASS, scenario and sensitivity analyses have been performed for four different types of biomass supply chains, as summarised below. The scenario analyses have the goal to illustrate the functionalities of the optimisation model, while the sensitivity