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a. TITLE: 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. Secondly, 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.

Keywords

Mathematical modelling, sludge supply, sludge management, sludge disposal, OPTIMASS

Abbreviations

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

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 et al., 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 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 miles 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 transshipment (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 optimization 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). Firstly, 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. Thirdly, 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 (Figure 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 analyses aim to investigate how the output of the model is altered by changes in the input.

1. The chain supplying grass from nature reserves and road verges (i.e. low input high diversity systems) to anaerobic digesters or composting facilities in the Limburg province (Belgium). OPTIMASS is used to optimise (1) the biomass flow in the existing supply chain, (2) the location of new conversion facilities in the existing chain and (3) the total configuration of the supply chain based on the net energy output, the economic profit, the greenhouse gas emissions or a combination of these objectives (De Meyer et al., 2015b, De Meyer et al., 2015c, De Meyer et al., 2016, Van Meerbeek et al., 2015).
2. The *Jatropha*-for-electricity supply chain in Southern Mali with the objective to minimise the total global warming impact of the chain. OPTIMASS is used to determine the optimal cultivation area(s) for *Jatropha* trees considering the emissions induced by the conversion from the original land use to the *Jatropha* plantation (result: subzones in the province of Sikasso, Southern Mali) (Almeida et al., under review).
3. The supply of green and other organic waste from about 421000 inhabitants to the composting facility of EcoWerf in Flemish Brabant (Belgium). OPTIMASS is used to investigate the feasibility of anaerobic digestion at the composting facility to digest the green waste prior to composting in terms of energy efficiency (result: feasible) and economic profit/loss (result: not profitable). (Ramaekers et al., 2015)
4. The local Flemish poplar-for-paper supply chain for the paper mill of Sappi in Lanaken (Flanders, Belgium). The extended multi-period optimisation model, t-OPTIMASS, (De Meyer et al., 2016) is used to investigate how the currently growing poplar plantations can be exploited in a sustainable way and how long poplar in Flanders can be used to meet poplar wood chips demand of Sappi considering different replanting strategies (De Meyer et al., 2015a).

In addition to the insights from the scenario and sensitivity analyses of these cases, this paper stresses the application of OPTIMASS to a sludge supply chain, a type of biomass with completely different characteristics and managed by totally different operations than the biomass types mentioned before. This enables the validation of the applicability of OPTIMASS to a sludge supply chain as well as the genericity of OPTIMASS. Also, this paper enables validation of the model by comparison of the economically optimised results with the results of a decision support system specifically developed for the municipal wastewater sludge processing chain studied in this paper (Section 5).

FIGURE 1: (a) High level process model to represent biomass-based supply chains (boxes correspond with operations and arrows indicate product flow between operations) (De Meyer et al., 2015b) and (b) the application to the considered sludge processing chain

In comparison to a typical biomass supply chain, the considered sludge processing chain involves no harvest and collection operations (Figure 1b). So, the constraints managing the flow and operation choice considering harvest and collection operations and treatment operations on the biomass production site are replaced by constraint (1). This constraint defines that all sludge produced in the WWTP's must be processed within the chain.

$$SUPmax_i^f = SUP_i^f \quad \forall i \in I, f \in F \quad (1)$$

with:

$SUPmax_i^f$ = Maximum quantity of a sludge product of type f produced at WWTP i (t_{DM} week⁻¹)

SUP_i^f = Quantity of a sludge product of type f delivered from WWTP i (t_{DM} week⁻¹)

i = index to define the wastewater treatment plant

f = index to define the type of sludge product

I = set of wastewater treatment plants (i)

F = set of sludge products (f)

2.2 Study area

To illustrate its applicability in defining the optimal combinations of treatments and disposal routes in a sludge supply chain, OPTIMASS is applied to minimise the overall GWImpact of the sludge processing chain from municipal WWTPs in a real, but unspecified, “region X” in north-western Europe. The required input data are derived from the real situation in region X, expanded with information from databases such as EcoInvent (EcoinventCentre, 2007) and expert opinions. Unfortunately, neither the input data nor the region can be mentioned in accordance with the agreed privacy regulations.

“Region X” counts 241 WWTP’s, comprising a total installed capacity of about 5000000 inhabitant equivalent (IE), and resulting in a weekly municipal wastewater sludge production of about 2000 tonnes of dry matter (t_{DM}). To handle the municipal wastewater sludge, 49 mechanical thickeners, 42 dewatering facilities and 17 anaerobic digesters with a total volume of about 60000 m³ are available. The municipal wastewater sludge processing network encompasses three drying plants to dry the municipal wastewater sludge (from 26 % to 93 % DM). After drying, sludge is transformed into pellets with a calorific value equivalent to that of brown coal (9 - 12 MJ/kg) enabling the use of sludge as industrial fuel. Three disposal facilities are operated and included in the analysis: i.e. one for mono-incineration, one for co-incineration and one in which sludge pellets are used in the cement industry to substitute charcoal. Figure 2 gives an overview of the WWTP network considered in this paper.

FIGURE 2: Municipal wastewater sludge processing network in “region X”. The size of the dots indicates the sludge production (t_{DM} per week) at the WWTP

2.3 Life cycle inventory analysis of the studied municipal wastewater sludge processing chain

To warrant a comprehensive evaluation of the sludge processing chain and the applicability in OPTIMASS, a life cycle inventory (LCI) is performed, identifying the possible product and operation types according to the conceptual model in figure 1 (De Meyer et al., 2015b). The chain, studied in this paper, starts when municipal wastewater sludge becomes available after wastewater treatment and ends in the disposal either at the mono-incinerator, the co-incinerator or the cement industry (Figure 3). First, the original municipal wastewater sludge is processed with mechanical or gravitary thickening methods to produce sludge of 5 to 8 % solids. The thickening treatment reduces transport costs and increases the efficiency of the anaerobic digester (Huybrechts and Dijkmans, 2001). After thickening, anaerobic digestion is regularly applied to stabilise the sludge and recover energy. Furthermore, mechanical dewatering intends to reduce the volume of sludge by the increase of the solids content up to 27 % on average. The dewatered sludge can be incinerated in the mono-incinerator and the co-incinerator. Prior to the usage of sludge as a fuel in the cement industry, the dewatered sludge must be dried to a solids content of 90 %, resulting in a calorific value of 9-12 MJ/kg.

FIGURE 3: Processing chain from municipal wastewater sludge as studied in this paper

In OPTIMASS, the quantities of original or treated sludge processed, transported and disposed of in the supply chain are expressed in tonnes dry matter per week (t_{DM} per week) since all treatments retain an equilibrium between dry weight of input and dry weight of output and data about weekly sludge production are available. An exception is anaerobic digestion in which an average dry matter loss of 24.7 % is considered (38% organic matter breakdown of sludge with 65% of the dry matter being organic). Since the volume of sludge is a determining factor in transport operations and decisions, the dry matter content of the transported sludge is taken into account.

One of the goals of this paper is to prove the concept that OPTIMASS is applicable to optimise sludge processing chains. To test and illustrate this concept, OPTIMASS is used to minimise the overall, weekly GWImpact (expressed in kg CO₂ eq) of the sludge processing chain from municipal WWTPs in “region X”. So, GWImpacts are inventoried for all operations involved in the processing chain (expressed in kg CO₂ eq per t_{DM}) (Figure 3) based on databases such as EcoInvent (Ecoinvent Centre, 2007) as well as peer reviewed literature (Werther et al. (1999), Nadal et al. (2009), Foley et al. (2010), Lederer et al. (2010), Mouri et al. (2010), Bravo et al. (2011), Carballa et al. (2011), Godin et al. (2012), Remy et al. (2013), Rodriguez et al. (2013), Valderrama et al. (2013)). Data on emissions and mineral substitution are retrieved from Remy (2009). Table 1 summarises the average GWImpact values for the different operation types. Also, economical (cost) data are available (expressed in € per t_{DM}) from the decision support system (DSS) specifically developed to optimise operational decisions in the municipal wastewater sludge processing chain in terms of minimal cost. Privacy regulations restrict the representation of the specific GWImpact values of each facility as well as the operation costs.

Table 1: Attribute values (averages) describing the operation types in the studied processing chain

Operation	Type	Subtype	Average global warming impact (kg CO ₂ eq t _{DM} ⁻¹ week ⁻¹)
Treatment	Thickening		22.2
	Anaerobic digestion		-185.5
	Mechanical dewatering	Centrifuge	65.4
		Filter press	33.1
		Belt filter press	41.0
Disposal	Thermal drying		619.0
	Mono-incineration		295.0
	Co-incineration		218.3
	Cement industry		-1041.7
Transport	Truck		0.03 kg CO ₂ eq t ⁻¹ week ⁻¹

Since the analysis starts when municipal wastewater sludge becomes available, the GWImpact related to sludge production is excluded. This inventory considers no other impact categories than GWImpact and does not take into account fixed GWImpacts related to for example facility construction. The cement industry is attributed a negative GWImpact due to the incorporation of the substitution of charcoal. Valorisation of residual heat in the co-incinerator has been neglected resulting in a positive GWImpact. Since the scope of this paper is not aimed at LCA, the GWImpact values are indicative, implying that scenario results are theoretically inspired to illustrate the functionalities of OPTIMASS. Due to privacy regulations, all results have been described proportionally in comparison to scenario 1.

3 Scenario analysis

3.1 Scenario 1: Optimal allocation and treatment of sludge in the current municipal wastewater sludge processing network in “region X”

Scenario 1 intends to determine the allocation and treatment of sludge in the current municipal wastewater sludge processing network in “region X” resulting in the minimal overall GWImpact (Figure 4). In addition, the economical data are used to define the allocation and treatment of sludge resulting in the cheapest municipal wastewater sludge processing chain (i.e. minimal cost) (Figure A.1 in Appendix A). This scenario requires that the binary variables, included in OPTIMASS to define the optimal treatment or disposal type at a location, are fixed to be 0 or 1 to define the (non-)existence of a treatment or disposal type at a certain location prior to optimisation.

FIGURE 4: Scenario 1: Allocation and treatment of sludge in the current municipal wastewater sludge processing chain in “region X” with minimal overall GWImpact defined by OPTIMASS

The differences between the supply chain resulting in the minimal GWImpact (Figure 4) and the supply chain resulting in the minimal cost (Figure A.1) are rather small. This is attributed to the fact that this scenario only allows optimisation of the product flow and the quantity of municipal wastewater sludge treated in facilities because the treatment types and disposal types on the locations are fixed prior to optimisation. Furthermore, constraint 1 defines that all municipal wastewater sludge must be routed in the chain which excludes the possibility to process less than the available quantity.

This results in a tight operation window. However, the results can be easily compared and deduction of the sensitivity to certain parameters (Section 4) is straightforward. In addition, this scenario addresses the optimisation of the tactical planning of the supply chain which is required weekly. Although the difference between the results might be small, weekly revision of the tactical plan is essential to make sure that the minimum and maximum capacities in the operation and disposal facilities are not trespassed and to consider (small) changes in municipal wastewater sludge production.

Since economical (cost) and environmental (GWImpact) data are available, OPTIMASS enables the immediate calculation of the total costs of the supply chain resulting in a minimal GWImpact (i.e. total costs of the supply chain represented in figure 4) and the total GWImpact of the supply chain resulting in a minimal cost (i.e. total GWImpact of the supply chain represented in figure A.1) (Figure 5). In comparison to the overall cost of the supply chain resulting in the minimal GWImpact (Figure 5(a) – (A)), the overall cost of the supply chain decreases with 1.3 % when minimising the overall cost of the supply chain (Figure 5(a) – (B)). This difference is mainly related to a reduction in transport cost. Due to the small dry matter content of original municipal wastewater sludge, the largest share in transport cost is related to the delivery of the original municipal wastewater sludge to the treatment facilities which is similar in both optimised chains. Therefore, the major reduction in transport costs relates to the allocation between treatment facilities and to the disposal facilities.

FIGURE 5: Scenario 1: Contribution of the operation types (a) to the total cost of the supply chain with minimal GWImpact (A) or with minimal cost (B) and (b) to the total GWImpact of the supply chain with minimal GWImpact (C) or with minimal cost (D). The supply chain with minimal GWImpact is the reference supply chain (100 %).

In comparison to the overall GWImpact of the supply chain resulting in the minimal cost (Figure 5(b) – (D)), the overall GWImpact of the supply chain decreases with 21.9 % when minimising the overall GWImpact of the supply chain (Figure 5(b) – (C)). In this GWImpact minimised supply chain, the higher GWImpact related to transport (2.3 %) is compensated by a decrease of the GWImpact related to treatment with 7.7 %. This decrease is mainly related to an increase in dewatered sludge and a redistribution of the sludge to be digested towards the anaerobic digesters characterised by the most favourable GWImpact. Although the GWImpact for drying increases slightly, it is compensated by the reduction in GWImpact due to disposal as sludge pellets. The distribution of dewatered sludge between the mono-incinerator and the co-incinerator is equal in both optimised supply chains, i.e. the minimum required capacity.

To validate OPTIMASS, the economically optimised results are compared with the outcome obtained with a decision support system (DSS) specifically developed to optimise operational decisions in the municipal wastewater sludge processing chain in terms of minimal cost. The results indicate that OPTIMASS transcends the overall cost of the supply chain with 4.1 % in comparison to the overall cost obtained with the in-house DSS. This difference is due to differences in allocation routes since the specific DSS excludes certain transport routes prior to the optimisation in contrast with OPTIMASS in which all possible routes between facilities are included. The difference in overall cost relates to the transport cost which can be explained by the different approach in OPTIMASS and the specific DSS. In the specific DSS, costs related to transport vary between transport equipment, routes and sludge type. In OPTIMASS, one average cost is defined to characterise all transport operations. Because the transport depends on the type of sludge to be transported, Therefore, the transport of original sludge (DM = 1.5 %) becomes decisive.

3.2 Scenario 2: Where to build a new thermal dryer(s)?

One of the promising strategies in sludge disposal is the use of (dried) sludge pellets as industrial fuel (Solisio and Dovi, 2013; Hara and Mino, 2008; European Commission, 2001). In scenario 1, the quantity of sludge disposed of at the cement industry is limited by the capacity of the installed dryers. On the other hand, the minimum required dewatered sludge at the incinerators limits the quantity of sludge available for conversion to sludge pellets. As a theoretical exercise, an increase in sludge production is considered. Considering an increase in sludge production of 20 % at all WWTPs, OPTIMASS is used to decide where to open one or more thermal dryers at current treatment sites or where to change the capacity of one or more installed dryers. To make sure that the production of sludge pellets is not limited by the maximum allowed capacity at the cement industry, the maximum capacity is set to 4000 ton per week (instead of 1000 ton per week). The resulting supply chain is presented in figure 6.

In comparison to scenario 1, OPTIMASS has defined one dryer to be added in the centre of “region X” and the upgrade of the two smaller dryers (capacity of 218 t_{DM} per week and 258 t_{DM} per week) to a capacity of 310 t_{DM} per week to minimise the GWImpact of the municipal wastewater sludge processing network. The extra drying capacity in combination with the assumed increased sludge production and the higher capacity at the cement industry results in an increase in sludge drying with 55 %. Although the extra drying increases the GWImpact related to treatment operations (41 %), the overall GWImpact of the supply chain almost halves. This decrease is mainly associated with the reduced GWImpact from the cement industry (76 %). Since constraint (1) defines that all sludge must be processed, the GWImpact related to transport increases with 33 % in which the largest increase is related to the transport of the larger quantity of original sludge.

FIGURE 6: Scenario 2: Where to build new thermal dryer(s)? – Minimal global warming impact as defined by OPTIMASS

The automated choice of OPTIMASS to upgrade the existing dryers is mainly defined by the requirement that the existing drying facilities cannot be closed and the beneficial GWImpact of the disposal at the cement industry that imposes to produce as much sludge pellets as possible. The automated choice of the extra drying facility in the centre of “region X” is mainly defined by its central location which is beneficial for transport operations and the existence of a thickening and dewatering plant and an anaerobic digester.

Although the maximum capacity of sludge pellets to be delivered at the cement industry is set to 4000 ton, only 1276 ton of sludge pellets is disposed of at the cement industry. This is directly related to the quantity of original municipal wastewater sludge produced in the WWTP's. By increasing the municipal wastewater sludge production, more dryers will be opened by OPTIMASS to produce more sludge pellets due to the beneficial combination in terms of GWImpact as long as the maximum capacity to thicken and dewater the sludge is sufficient to process all original sludge.

4 Sensitivity analysis

Although uncertainty is inevitable in decision making (Shabani et al., 1998), OPTIMASS, as a deterministic model, cannot consider this uncertainty. An appropriate way to address this limitation is to perform a sensitivity analysis. This paper investigates the effect of seasonal changes in sludge quantities on the overall GWImpact and the configuration of the supply chain (Section 4.1). In addition, the effect of the GWImpact of the cement industry on the definition of the optimal supply chain is investigated (Section 4.2).

4.1 Sensitivity to uncertainty in municipal wastewater sludge production

Due to seasonal variation, the municipal wastewater sludge production varies between 70 % and 130 % of the sludge production in scenario 1. To investigate the effect of changes in municipal wastewater sludge production, 5 scenarios are optimised considering a certain percentage of the sludge production ($SUPmax_i^f$ in constraint (1)) (ranging from very low (70 %) to low (85 %), normal (100 %), high (115 %) and very high (130 %)) to be processed in the current municipal wastewater sludge processing chain. This implies that the normal scenario (100 %) equals scenario 1. For each scenario, the contribution of transport, treatment and disposal operations to the overall GWImpact of the optimised chain is summarised in figure 7.

FIGURE 7: Effect of changes in municipal wastewater sludge production (70 % - 130 %) on the global warming impact and configuration of the current municipal wastewater sludge processing chain in “region X”

In comparison to the other scenarios, the normal scenario (100 %) results in the lowest overall GWImpact (Figure 7). Since treatment and conversion locations are fixed in this sensitivity analysis, this implies that the current municipal wastewater sludge processing network is well adapted to process the 100 % sludge supply. In this scenario, the minimum required quantity of sludge in the mono-incinerator and the co-incinerator are precisely met and the remaining sludge is disposed of at the cement industry. This is also the case in the scenario in which 85 % sludge production is available. Due to the lower sludge availability, less sludge can be disposed of at the cement industry inducing a raise in GWImpact related to the total sludge disposal. This also relates to the lower GWImpact of treatment operations because a smaller quantity of municipal wastewater sludge must be dried. If only 70 % of the sludge production must be processed, proportionally less sludge is disposed at the cement industry in comparison to the incinerators. Therefore, the disposal of sludge receives a positive GWImpact value. This results in a reduced quantity of sludge dried in the supply chain due to which the negative GWImpact value related to anaerobic digestion becomes decisive.

In the case of an increase in municipal wastewater sludge production (115 %), the overall GWImpact increases in comparison to scenario 1 (100 %). This increase is related to the larger quantity of sludge co-incinerated. Since the capacity of the drying facilities is met, no extra sludge can be dried to be disposed of at the cement industry. This induces an increase in GWImpact related to disposal because the larger quantity of sludge must be processed at the co-incinerator. In all scenarios, only the minimum required quantity of sludge is assigned to the mono-incinerator because it is the disposal option with the highest GWImpact. An optimised supply chain cannot be defined for scenarios assuming a sludge production higher than 120 % of the original value. In this case the amount of sludge to be processed in the chain transcends the total capacity of the mechanical and gravitary thickeners in the current supply chain. Due to constraint (1) and the requirement that all sludge must be processed in the chain it is not possible to get a feasible solution.

Finally, the GWImpact related to transport operations changes approximately proportionally to the change in sludge production. The largest increase is related to the transport from WWTP's because constraint (1) obliges all municipal wastewater sludge to be processed in the chain involving the transport of more original municipal wastewater sludge to the treatment plants.

4.2 Sensitivity to the global warming impact of the cement industry

Although thermal drying is required, one of the most promising alternative strategies for the disposal of municipal wastewater sludge is its transformation into pellets to be used as a fuel in cement factories (Solisio and Dovi, 2013). Because the GWImpact values related to the use of dried sludge in the cement industry differ between literature sources, the sensitivity of the overall GWImpact of the optimised supply chain and the distribution of sludge between the 3 disposal facilities to the GWImpact of this disposal possibility is investigated. First, OPTIMASS is used to define the optimal

sludge processing chain in which the GWImpact value for the cement industry has changed between 0 kg CO₂ per t_{DM} and – 1300 kg CO₂ per t_{DM}. Based on these results, the intervals of GWImpact values for the cement industry have been determined that result in a shift in sludge distribution.

FIGURE 8: Sensitivity of allocation pattern between disposal options and sensitivity of overall GWImpact to changes in the GWImpact value related to the cement industry

In the results, the GWImpact related to transport is similar for all supply chains. So, changes in the overall GWImpact due to the adapted GWImpact of the cement industry are defined by changes in the distribution of municipal wastewater sludge between the treatment and disposal facilities. Figure 8 highlights 5 major intervals: i.e. $[-323 \text{ kg CO}_2 \text{ per t}_{\text{DM}}, +\infty]$, $[-341 \text{ kg CO}_2 \text{ per t}_{\text{DM}}, -324 \text{ kg CO}_2 \text{ per t}_{\text{DM}}]$, $[-566 \text{ kg CO}_2 \text{ per t}_{\text{DM}}, -342 \text{ kg CO}_2 \text{ per t}_{\text{DM}}]$, $[-569 \text{ kg CO}_2 \text{ per t}_{\text{DM}}, -567 \text{ kg CO}_2 \text{ per t}_{\text{DM}}]$ and $[-\infty, -570 \text{ kg CO}_2 \text{ per t}_{\text{DM}}]$. In general, the delivery of dewatered sludge to the mono-incinerator is limited to the minimum required quantity of sludge to be delivered. So, changes within the processing chain relate to a redistribution of sludge between the co-incinerator and the cement industry.

With a GWImpact value of the cement industry higher than $-324 \text{ kg CO}_2 \text{ per t}_{\text{DM}}$, no sludge pellets are produced to be delivered at the cement industry. This implies that all sludge is dewatered for disposal at the incinerators which results in a high GWImpact related to the disposal of sludge. As in previous scenarios, the minimum required capacity is met at the mono-incinerator. The residual sludge is delivered at the co-incinerator. Although the GWImpact related to treatment of sludge is negative due to the anaerobic digestion of sludge and a lack of drying operations, the overall GWImpact is the highest in this interval. The optimal allocation and treatment of sludge as well as the overall GWImpact of the optimal supply chains are identical in this interval.

From a GWImpact value of -324 kg CO₂ per t_{DM}, sludge pellets are produced in the drying facilities to be delivered to the cement industry. Until the value of -342 kg CO₂ per t_{DM}, the quantity of sludge disposed at the cement industry rises gradually to a distribution of 30 % at the expense of the co-incinerator. A GWImpact value between -566 kg CO₂ per t_{DM} and -342 kg CO₂ per t_{DM} results in a steady sludge distribution of 26 % to the mono-incinerator, 42 % to the co-incinerator and 32 % to the cement industry. Within this interval the allocation and treatment of sludge within the current supply chain is unchanged. The change in overall GWImpact is directly related to the changed GWImpact of the cement industry.

In the small interval between -569 kg CO₂ per t_{DM} and -567 kg CO₂ per t_{DM}, the delivery to the cement industry rises from the steady 32 % to above 40 % with a steady state on 47 % with a GWImpact value of -570 kg CO₂ per t_{DM}. From this point, the configuration of the sludge processing chain is unchanged because the quantity of sludge pellets delivered at the cement industry (47%) meets its maximum possible quantity considering the minimum required quantities of dewatered sludge to be delivered at the incinerators as defined by contract. The overall GWImpact decreases in direct relation to the changing GWImpact of the cement industry. In this interval, the GWImpact value related to the disposal at the cement industry transcend the GWImpact related to the required drying treatment. Furthermore, from a global warming impact of -821 kg CO₂ per t_{DM}, the studied sludge supply chain is not longer CO₂ neutral.

5 Discussion

A critical point in the implementation of OPTIMASS is the difficulty to identify reliable quantitative values of GWImpact for the various model parameters. To prove that the implementation of a biomass supply chain optimisation model to optimise the sludge processing chain from municipal WWTPs is meaningful, GWImpact values are derived from data in databases and literature based on a preliminary LCI. This inventory considers no other impact categories than GWImpact (e.g. ozone formation, eutrophication, ...) and does not take into account fixed GWImpacts related to for example construction. In this LCI, the cement industry is attributed a negative GWImpact due to the incorporation of the replacement of charcoal. However, valorisation of residual heat in the co-incinerator has been neglected resulting in a positive GWImpact. A change in this approach can change the distribution of sludge between the disposal facilities which results in an adjusted distribution of sludge between the treatment facilities in the supply chain. Additionally, it has not been considered whether or not the dryers in the supply chain use residual heat. The use of residual heat can reduce the GWImpact related to the drying facilities which increases the preference to deliver sludge pellets to the cement industry. An extensive LCA would improve the approach of reality. Unfortunately such an LCA is beyond the scope of this paper and a field of research on its own.

The results of the scenario and sensitivity analyses indicate that the decision process, to minimise the overall GWImpact of the sludge processing chain, is partially driven by the characteristics of the disposal facilities. On the one hand, this is due to constraint (1) defining that all municipal wastewater sludge must be processed within the chain while on the other hand, a minimum quantity of sludge is requested at the disposal options. The minimum required capacity of the incinerators forces a certain quantity of municipal wastewater sludge to be disposed of here which is not available for disposal at the cement industry. This implies that the supply chain is sensitive to the impact values defined for each of the disposal facilities. The analysis investigating the sensitivity of the supply chain to changes in the GWImpact value related to the cement industry results in the robust interval $[-\infty, -570 \text{ kg CO}_2 \text{ per } t_{DM}]$ in which the configuration of the supply chain is unchanged. However, this interval relates to the GWImpact defined for the incinerators. A smaller GWImpact related to the incinerators will require a more negative GWImpact related to the cement industry to make disposal at the cement industry beneficial.

To investigate the possibility of OPTIMASS to be applied to the sludge processing chain and to validate OPTIMASS in general, the result of scenario 1 (minimising cost) has been compared with the result obtained with a decision support system (DSS) specifically developed to optimise operational decisions in the municipal wastewater sludge processing chain in terms of minimal cost. Results indicate that OPTIMASS transcends the overall costs of the total supply chain mainly due to a different approach to calculate the transport costs. Indeed the specific DSS varies the transport costs based on transport equipment, routes and sludge type while OPTIMASS uses an average cost. However, it can be decided that the OPTIMASS approach is confirmed by the close correspondence between the results.

6 Conclusions

In sludge management, sludge is increasingly perceived as a marketable product rather than as a waste material. This awareness induces the need for a decision environment to select the optimal combinations of treatments and disposal routes from the different alternatives to ensure that the right goods are conveyed safely to the correct place at the right time at the lowest possible cost considering the whole chain. Through the application of OPTIMASS, a generic mathematical model developed for the optimisation of all kinds of biomass supply chains, to minimise the GWImpact of the municipal wastewater sludge processing chain in “region X” this paper shows that OPTIMASS, provides such a decision environment.

Two scenarios have been addressed by means of OPTIMASS: (1) the definition of the optimal allocation and treatment of municipal wastewater sludge within the current network, and (2) the definition of the optimal location(s) for new drying facilities in this chain. The results indicate that transport operations mainly influence the overall cost while the overall GWImpact is mainly influenced by the disposal options of the sludge. In addition, the results reflect some general characteristics of the sludge processing chain: e.g. a large part in transport GWImpact/cost is assigned to the transport of untreated sludge and new treatment (drying) facilities are located at larger WWTPs.

OPTIMASS can be used as an inspiring tool to investigate the influence of changes in the capacity agreements with the disposal facilities, the influence of introducing new treatment technologies or disposal facilities in the processing chain, etc.

OPTIMASS, as applied in this paper, optimises the processing chain over one given time period. However, as presented in section 4.1, the optimal sludge processing chain differs according to the quantity of incoming municipal wastewater sludge which changes over time. To determine the optimal location and technology of new treatment and/or disposal facilities it is necessary to consider the changes in sludge production over time to make sure the capacity constraints are met and sufficient capacity is available to process the sludge peaks. This endorses opportunities for future research in which apply the multi-period MILP model, t-OPTIMASS would be involved, (De Meyer et al., 2016). Additionally, the MILP model can be seen as the base for multi-objective optimisation. This final topic is part of a paper recently published by the authors in which the mathematical model is combined in a compromise programming approach to define the optimal supply chain based on a trade-off between different objectives (De Meyer et al., 2015c).

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Appendix A. Visualisation of the results

FIGURE A.1: Allocation and treatment of sludge in the current municipal wastewater sludge processing chain in “region X” resulting in minimal overall cost calculated with OPTIMASS

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