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Considering biomass growth and regeneration in the optimisation of biomass supply chains

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ABSTRACT

This paper presents t-OPTIMASS, a multi-period mixed integer linear programming model to optimise strategic and tactical decisions in all kinds of biomass supply chains taking into account the geographical fragmentation and temporal availability of biomass and changing biomass characteristics due to handling operations. Unlike existing models, t-OPTIMASS considers the growth and regeneration of biomass to determine the optimal harvesting moment(s). t-OPTIMASS is demonstrated based on the use of grass from nature reserves and road verges to substitute maize in the digestion mixture converted in the currently available wet anaerobic digesters or potential dry anaerobic digesters in Limburg (Belgium).

The results highlight that the decision process is driven by the requirements imposed to the characteristics of the biomass to be converted at the conversion facility. The harvesting moment is defined and pre-treatment operations are introduced to make sure that biomass is delivered with characteristics that fit best these requirements. The analyses indicate that storage facilities are indispensable to deal with the temporal availability of biomass, the conflicting temporal demand and the required constant feeding of the digesters. t-OPTIMASS allows users, interested in macro-analysis, to define biomass potentials, to support policy decisions, to evaluate the feasibility of new facilities, etc.

1. Introduction

To meet the world's ever increasing energy consumption, biomass is considered as an attractive feedstock for renewable energy because it is abundantly present and, in comparison to most other renewable energy sources, it can be stored to generate different forms of energy (i.e. electricity, heat and biofuels) on demand [1,2]. However, biomass is still a source of energy that is generally underutilised due to uncertainties related to weather variability and market conditions [3] and to barriers induced by the complex supply chain [4,3]. An increasing number of research papers report on the combination of supply chain management and operational research in the field of bioenergy systems to tackle the challenge to develop a sustainable bioenergy industry considering the interrelated decisions within the supply chain, the complex hierarchy in decision making and the role of each actor within the chain [1,3,5–8]. Most models have been developed to (economically) optimise long-term, usually investment intensive decisions pertaining to the design of the biomass supply network (e.g., sourcing of biomass, choice of capacity, technology and location of storage, pre-treatment and conversion facilities) [8]. These spatial optimisation models consider the spatial fragmentation of the biomass production units and its typical characteristics such as a high moisture content, low bulk density and low heating value.

Furthermore, the seasonal availability of biomass makes the biomass supply chain different from those typically addressed in supply chain management [2]. This introduces the challenge to

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address the temporal availability of biomass, the possibly conflicting temporal energy demand and the temporally constant feeding requirement of the conversion facilities [2]. Multi-period mixed integer linear programming (MILP) models have been proposed to optimise the strategic and tactical plans resulting in the minimal overall chain cost throughout the planning horizon of one year to tune the seasonal availability of biomass to meet the conflicting, seasonal energy demand [9–16]. These models consider the seasonal biomass availability and energy demand by defining the quantity of available biomass and the energy demand in each time period (usually months) as a fixed value. These models highlight the gradual installation of storage and conversion capacities over time highlighting the need for the incorporation of time into strategic decision making [17]. Similar multi-period MILP models have been presented to minimise the overall chain cost within a planning horizon of multiple years [17–21]. In contrast with the models that consider the monthly availability of biomass, these models divide their planning horizon into 1 year time periods.

Apart from its seasonal availability, biomass is also characterised by a growth cycle. This implies that, within the growth season, a new growth cycle starts after harvest enabling multiple harvesting moments throughout the planning horizon. So, the moment of harvest does not only determine the availability and characteristics of biomass at that moment, but also influences the availability and characteristics of tomorrow's biomass. To use biomass as a sustainable, renewable source of energy, the required constant supply of biomass must balance the accretion of biomass in the field [22]. Also, the moment of harvesting should be adapted to fit best the requirements of storage and conversion facilities considering the required continuous supply at the conversion facility, the changing energy demand, statutory harvesting moments, etc. This suggests that the growth and regeneration of biomass is decisive in the design and management of the supply chain. However, to the best of our knowledge, these issues are not incorporated in the published models optimising biomass supply chains strategically and/or tactically. Only recently, Yu et al. (2014) consider forest regeneration, the cutting cycle and biomass degradation during storage in an operational planning model to weekly assign harvesting teams and to allocate the biomass flows resulting in a minimal cost over the 1-year planning horizon [22].

This paper describes the expansion of the spatially oriented mixed integer linear programming (MILP) model, OPTIMASS [23], to consider the growth and regeneration of biomass in the strategic/tactical decision process (Section 2). OPTIMASS has been selected because the model embraces the upstream biomass supply chain in a comprehensive way which makes it applicable to all kinds of biomass supply chains. OPTIMASS takes into account changes in product characteristics due to handling operations. A similar approach can be applied to define changes in characteristics due to growth or regeneration. In comparison to OPTIMASS as a spatial optimisation model, this spatio-temporal expansion enables the definition of the optimal harvesting moment and the gradual installation of handling facilities. This paper illustrates the functionalities and possibilities of the model by the application to a supply chain based on biomass derived from low input high diversity (LIHD) systems to anaerobic digesters in the Limburg province (Belgium) (Section 3). OPTIMASS is applied to determine the optimal configuration of the supply chain resulting in the maximal net energy output considering (1) the currently present wet anaerobic digesters and (2) potential dry anaerobic digesters (Section 4). A sensitivity analysis is performed to determine the impact on the supply chain of (1) changes in biomass production and (2) changes in the energy input from the use of extra products (Section 5). These analyses result in an evaluation of the behaviour of OPTIMASS as spatio-temporal optimisation model and the definition of opportunities for its further elaboration (Sections 6 and 7).

2. Materials and methods

2.1. OPTIMASS

The deterministic, static, multi-echelon, multi-product MILP model, OPTIMASS, is meant to optimise the strategic (i.e. design) and tactical (i.e. logistics planning) decisions in all kinds of biomass supply chains based on the maximal net energy output, maximal profit or minimal global warming potential [23] or a combination of these objectives [24]. To embrace biomass supply chains in a comprehensive way, OPTIMASS is based on the results of a generic cradle-to-gate analysis of the upstream biomass supply chain highlighting six key operations from the point of harvesting raw biomass materials to the delivery of the biomass to the conversion facility: i.e. biomass production, harvest, collection, pre-treatment, storage and conversion to bioenergy (Fig. 1) [25].

OPTIMASS approaches the problem as a multi-stage capacitated facility location planning problem [26] in which at each facility the characteristics of the biomass product can change due to handling operations. This translates into integer variables defining the strategic decisions (cfr. boxes in Fig. 1) and continuous variables defining the tactical decisions (cfr. arrows in Fig. 1). Unlike (most) other models, OPTIMASS takes into account changes in product type (and characteristics) due to handling operations. Therefore, transformation coefficients are created that define the transition from one product type to another. In a similar way, OPTIMASS considers the re-injection of by-products from the conversion process in the biomass supply chain. A complete description is given in De Meyer et al. (2015) [23]. In that paper, the analysis of OPTIMASS for sensitivity to changes in biomass production and in energy demand highlights the need for a multi-period optimisation

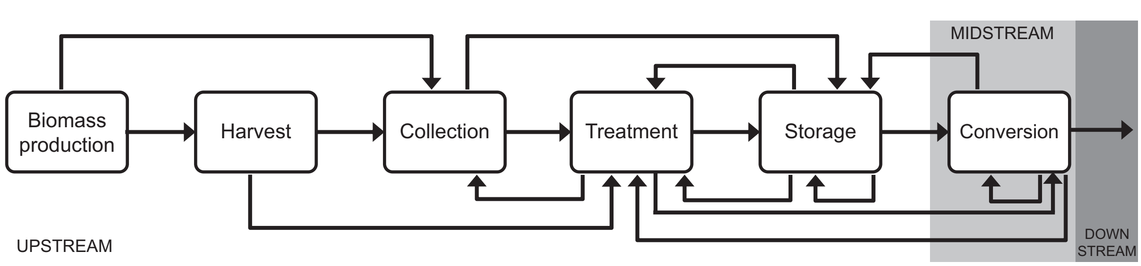

Fig. 1. High level process model of the biomass supply chain representing the sequence of operations. The boxes represent the 6 key operation types distinguished in the upstream segment while the arrows indicate the possible material flows between the key operations [23].

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approach to define a network that can cope with these variations in time [23].

2.2. Upgrade to a spatio-temporal MILP model considering biomass growth and regeneration

The multi-period problem can be seen as a network consisting of a number of layers in which each layer represents a time period in which OPTIMASS, as presented in De Meyer et al. (2015) [23], is applicable (Fig. 2). In each time period t, the arcs that connect the nodes represent product flow in that period (solid arrow in Fig. 2). To support optimisation of the biomass network over a certain planning horizon consisting of multiple time periods, two consecutive time periods (t and t + 1) must be linked. Therefore, inventory arcs are introduced at storage sites (j,l) and conversion sites (k,m) fine-tuning the transfer of biomass from one time period to the other (dashed arrows in Fig. 2).

2.2.1. Regulating biomass growth and regeneration

To consider biomass growth and regeneration, different product types must be defined to represent biomass in each of the possible growth stages in terms of the typical characteristics (e.g., harvestable biomass production, biogas production, particle size, moisture content). These characteristics are derived from a growth model prior to the optimisation. The choice of a specific growth model depends on the biomass type, the data availability, the required time accuracy, etc. In the first time period, the maximum available quantity of each product type f at each biomass production site i ($SUPmax_{it}^{f}$) is defined by constraint (1a). This constraint relies on the data on available area of each biomass type at each biomass production site ($AREA_i^f$). This implies that one biomass production site can contain biomass of different types and growth stages. In the subsequent time periods, the maximum available quantity of each product type f at each biomass production site i ($SUPmax_{it}^{f}$) depends on the quantity of product type f harvested in the previous period (sH_{it-1}^{f}) and the quantity of product type f not harvested in the previous period (sNH_{it-1}^{f}) (constraint (1b)). Transformation coefficients define the changes in product type (and therefore growth stage) due to the harvest (γ_H^{fr}) and due to the growth (γ_{NH}^{fr}) considering the change in harvestable biomass production. Constraint (2) ensures that the mass balance within one time period is maintained. To ensure the readability of the paper, the explanation of the symbols is given in Appendix B.

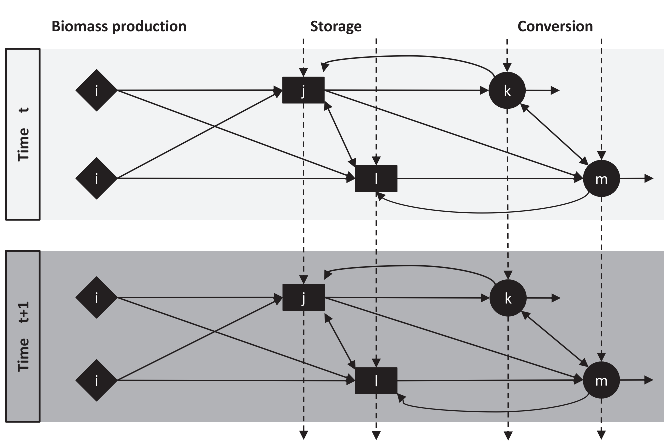

Fig. 2. Illustration of the multi-period approach considering the product flow between biomass production sites (i), storage sites (j,l) and conversion sites (k,m) (solid arrows) and between time periods (dashed arrows). The grey shaded areas differentiate between time periods in which OPTIMASS [23] is applicable.

$$SUPmax_{it}^{f} = \begin{cases} AREA_i^f \cdot HBP^f & \forall i \in I, f \in F, t = 1 \quad (a) \\ \sum_r \left(sH_{it-1}^{r} \cdot \gamma_H^{rf} \right) + \sum_r \left(sNH_{it-1}^{r} \cdot \gamma_{NH}^{rf} \right) & \forall i \in I, r \in F, t > 1 \quad (b) \end{cases} \tag{1}$$

$$SUPmax_{it}^{f} = sH_{it}^{f} + sNH_{it}^{f} \quad \forall i \in I, f \in F, t \in T \tag{2}$$

2.2.2. Temporal energy demand

Similar to the multi-period models described in the introduction, the energy demand in each period (t) is a fixed value (D_t^o). Constraint (3) ensures that in each time period the total demand for each type of bioenergy (e.g., heat, electricity) is met. The production of an energy surplus is allowed by constraint (4).

$$Esurplus_t^o = \sum_{k \in K} \sum_{c \in C} \left(E_{kt}^{co} \right) - D_t^o \quad \forall o \in O, t \in T \tag{3}$$

$$Esurplus_t^o \leqslant Q^o \cdot D_t^o \quad \forall o \in O, t \in T \tag{4}$$

2.2.3. Connection between time periods

The inventory arcs (dashed arrows in Fig. 2) create the bridge between two subsequent time periods. These inventory arcs are represented by inventory variables which define the amount of product type f transferred from one period to the next at the storage facility (I_{jt}^{fs}) and conversion facility (I_{kt}^{fc}). In constraints (5) and (6), the inventory is defined by the inventory of the previous period (I_{jt-1}^{fs} and I_{kt-1}^{fc}), the quantity of product delivered at the storage and conversion facility (X_{injt}^{fs} and X_{ct}^{fk}) minus the quantity of product departing from the storage facility (X_{outjt}^{fs}) or converted at the conversion facility (C_{ct}^{fk}). In addition, pre-treatment operations can occur at these facilities leading to changes of product characteristics. So, the mass balance considers the quantity of product type f entering a pre-treatment operation at that facility (X_{jt}^{fsp} and X_{kt}^{fcp}) and the quantity of the product type created after pre-treatment (P_{jt}^{spf} and P_{kt}^{cpf}). To consider the supply chain in a circular way, the inventory of the final period (T) is available in the first period (t = 1) (constraint (5a) and constraint (6a)). A steady state regime is assumed which implies that the harvestable biomass production and energy demand change according to the same seasonal pattern every year. However, this cyclicity assumption is not required and can be removed by taking out out the variables I_{jT}^{fs} and I_{cT}^{fk} from equations (5a) and (6a).

$$I_{jt}^{fs} = \begin{cases} I_{jT}^{fs} + X_{injt}^{fs} - \sum_p X_{injt}^{fsp} + \sum_p P_{jt}^{spf} - \dfrac{X_{outjt}^{fs}}{1 - \Delta^s} & \forall f \in F, j \in J, s \in S, t = 1 \quad (a) \\ I_{jt-1}^{fs} + X_{injt}^{fs} - \sum_p X_{injt}^{fsp} + \sum_p P_{jt}^{spf} - \dfrac{X_{outjt}^{fs}}{1 - \Delta^s} & \forall f \in F, j \in J, s \in S, t > 1 \quad (b) \end{cases} \tag{5}$$

$$I_{ct}^{fk}=\begin{cases} I_{cT}^{fk}+X_{ct}^{fk}-\sum_{p}X_{kt}^{fcp}+\sum_{p}P_{kt}^{cpf}-C_{ct}^{fk} \\ \qquad \forall f\in F,k\in K,c\in C,t\in T \quad (a) \\ I_{ct-1}^{fk}+X_{ct}^{fk}-\sum_{p}X_{kt}^{fcp}+\sum_{p}P_{kt}^{cpf}-C_{ct}^{fk} \\ \qquad \forall f\in F,k\in K,c\in C,t>1 \quad (b) \end{cases} \tag{6}$$

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3. Case study description

Anaerobic digesters can handle various types of biomass and waste [27]. In most cases, co-digestion of several product types even leads to superior digestion efficiencies [27,28]. To not compete with food crops in agricultural land usage, a potential promising role is reserved for biomass from low input high diversity (LIHD) systems such as (semi-) natural grasslands, small landscape elements, etc. [29–40]. Therefore, the functionalities and behaviour of the spatio-temporal t-OPTIMASS are demonstrated based on the potential of mesotrophic grass from nature reserves and grass from road verges to feed anaerobic digesters in the Limburg province (2422 km^2) (Belgium) (Fig. 4). The possible operations in the supply chain, as considered in this case study, are presented in Fig. 3. The attributes and attribute values are defined for each product type (Table C.1) and operation type (Table C.2). Data and assumptions are retrieved from databases such as EcoInvent [41] or peer-reviewed literature and expert opinions.

The locations and corresponding areas of the mesotrophic grasslands and road verges are derived from the biological valuation map of Limburg (Belgium) [42] represented by a grid of 1 km by 1 km resolution as described in Van Meerbeek et al. (2015) [54]. To allow the graphic display of the results in an orderly manner, the 1 km by 1 km grid is resampled to a 5 km × 5 km grid in which the area of the biomass sites equals the sum of the areas of the 1 km by 1 km grid cells that fall within the 5 km by 5 km cell (Fig. 4). In Belgium, the road verge decree of 1984 (Bermbesluit 27/06/84) limits the possible moments to harvest to one mowing period after June 15th and a second mowing period after September 15th. This implies that the 1-year time horizon can be divided into 5 time periods: January to May (TP1), June–July (TP2), August (TP3), September–October (TP4) and November–December (TP5) (Fig. 5). So, grass from mesotrophic grasslands and road verges can only be mown in TP2, in TP4 or both (TP24). The model considers the time-dependent biomass yield, biogas yield and particle size to define the optimal harvesting moment [43,40,30] (Table C.1).

All 13 wet anaerobic digesters currently available in Limburg are considered in the LIHD-for-biogas network (Fig. 4). Based on the capacity, three types of digesters are distinguished: i.e. 8 micro anaerobic digesters (MAD), 4 farm scale anaerobic digesters (FAD) and 1 industrial anaerobic digester (IAD) (Table C.2). The digesters are characterised by a continuous feeding regime in which fresh material is added on a frequent basis and the different stages of the digestion process occur simultaneously. This results in a constant biogas production at each digester. It is assumed that in all digesters the digestion mixture is composed of organic household waste (0–20%), maize (10–20%) and pig slurry (50–80 %) (Table C.1). For these "extra products", OPTIMASS determines the optimal quantity of product used in each conversion facility considering a pre-defined energy input related to the delivery of the extra product to the digester (Table C.1), the maximum available quantity of the product and product requirements in the conversion facility (Table C.2) [23]. The supply chain of these products is not optimised [24]. LIHD biomass, of which the supply chain is optimised in this case study, is considered to substitute maize with a required minimum of 5% to an allowed maximum of 20% of the total conversion mixture [29].

At the conversion locations, the produced biogas is fed into a combined heat and power (CHP) installation to generate heat and electricity. The electricity and heat output at each facility1 in each time period (E_{kt}^{co}) are defined by constraint (7) and are based on the quantity of biomass products and extra products in the conversion mixture (U_{kt}^{fc} and UX_{kt}^{ec}), the biogas yield of the biomass products and extra products in the conversion mixture (ρ^f and ρ^e) (Table C.1), the average calorific value of biogas (assumed to be 6 kWh m^{-3}*biogas*) and the efficiency of the conversion facilities (η^{co}) (Table C.2).

$$E_{kt}^{co}=\left[\sum_{f}\left(\eta^{co}\bullet U_{kt}^{fc}\bullet CV^{biogas}\bullet\rho^{f}\right)+\sum_{e}\left(\eta^{co}\bullet UX_{kt}^{ec}\bullet CV^{biogas}\bullet\rho^{e}\right)\right]$$
$$\forall k\in K,c\in C,o\in O,t\in T \tag{7}$$

As pointed out in section 2.2.2, t-OPTIMASS includes a demand constraint to ensure that the demand for each bioenergy type is met in each time period by all conversion facilities. In this case study, the bioenergy demand has been constrained in two ways. First, it is defined that the anaerobic digesters must generate at least 90% of their annual electricity capacity. The demand corresponds to the needs of ±17000 households (considering an average electricity consumption of 3500 kWh per household per year) which is about 5% of the households in Limburg. Secondly, it is defined that the electric demand in each month (Fig. 5) must be

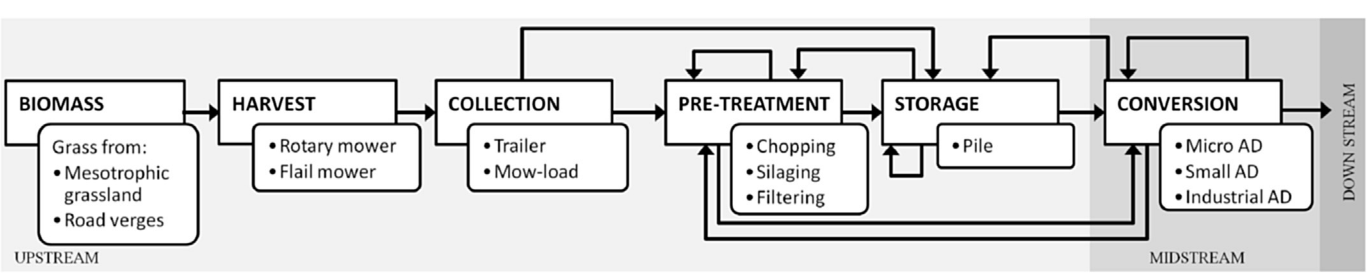

Fig. 3. High level process model of the studied LIHD-for-biogas supply chain corresponding to the system boundaries. The angular boxes represent the key operation types while the rounded boxes summarise the potential operation types considered in this case study. The arrows indicate the possible material flows.

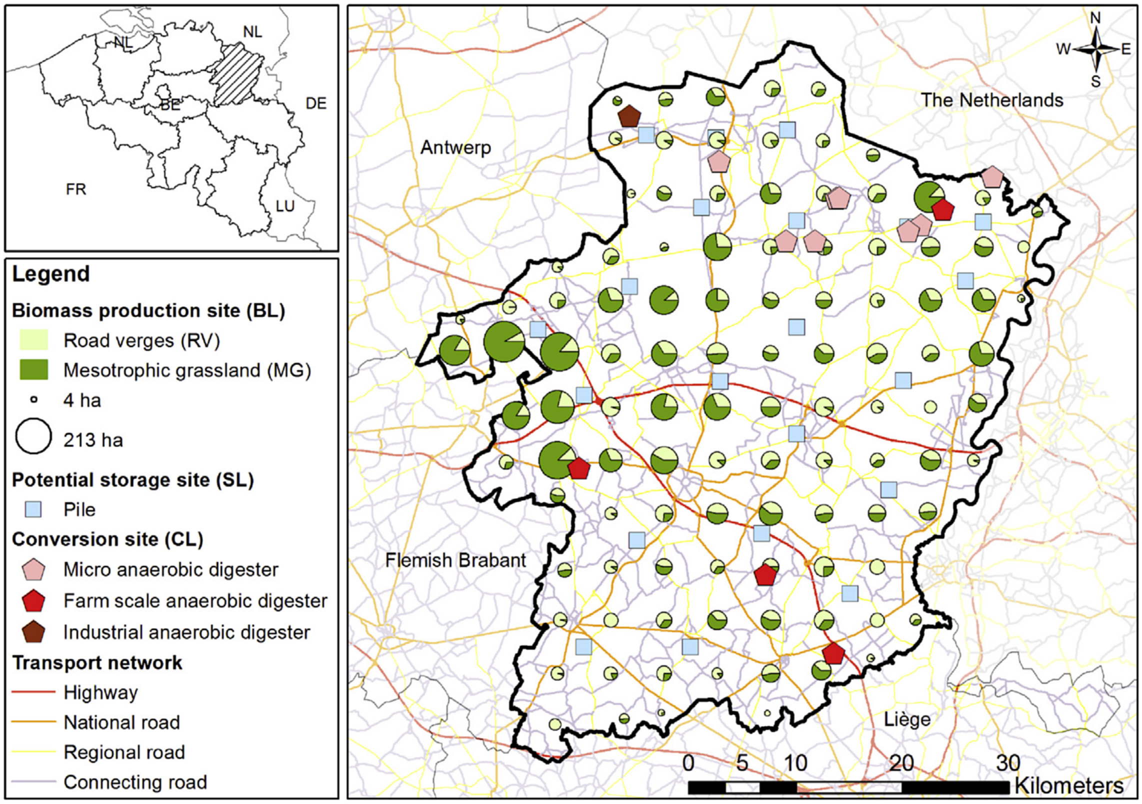

Fig. 4. LIHD-for-biogas network in the Limburg province (without the municipality of Voeren) considered in this case study. The size of a ring represents the relative size of the biomass production sites upscaled to the 5 km × 5 km grid. The pie chart representation gives an indication of the fraction of each biomass type within the cell.

met at least considering the continuous feeding rate requirement at the biogas plants and a constant biogas production (D_t^o in constraint 3 derived from Fig. 5).

To deal with the peak flow of harvested biomass in TP2 and TP4, long-term storage is needed [44,30]. The preferred form of storage is ensilaging, since grass can be preserved with minimal loss [30] and the treatment is proven to have relatively little effect on specific biogas yield [44] (Table C.1). Since biomass from mesotrophic grasslands can only be harvested with the rotary mower, chopping of silage prior to digestion is required. This is not the case for grass from road verges because the harvesting operation with the flail mower results in biomass with sufficiently small particle size (Table C.1). However, grass from road verges is usually contaminated with litter and sand causing all kinds of problems in the digester. Therefore, filtering and washing of grass from road verges prior to ensilaging or digestion is required [43]. Due to a lack of real-world data, the storage sites are defined on the most likely locations in Limburg considering the location of highway access points, the nearness of conversion sites and the density of biomass production sites (Fig. 4). The number of storage sites is limited to 21 which is a trade-off between the clear display of the results and the illustration of the functionalities. A storage site houses an open-air pile with a capacity of 1500 m^3.

The real-world transport distances are retrieved from the Navstreet database [46]. For truck transport, the shortest path between sites (d_{xy}^z) are determined considering the driving directions and restrictions from Navstreet. For transport by tractor, it is assumed that tractors can not access the highway, but are allowed to access all other roads. The characteristics of the transport operations are included in table C.2.

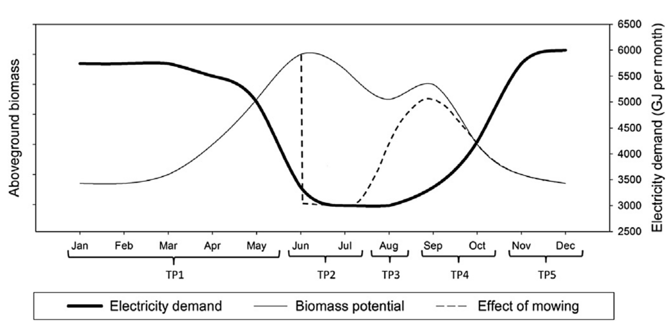

Fig. 5. Monthly changes in electric demand and biomass potential with indication of the effect of mowing in TP2 on the biomass potential in TP4 (based on [45]).

4. Scenario analysis

4.1. Scenario 1: optimising the use of the current infrastructure

This scenario (1A) considers the LIHD biomass supply chain including the currently present wet anaerobic digesters. This implies that the binary variables (Y_{kt}^c) are pre-set to 0 or 1 to define the (non-)existence of a conversion type at each conversion site in each period. The resulting optimal supply chain is presented in Fig. 6 in which 14 (out of 21) storage facilities are opened. In this supply chain, 220043 GJ of electricity and 305417 GJ of heat are produced per year. Around 42% of the total energy output is needed to perform all operations in the chain (Scenario 1A in Table 1).

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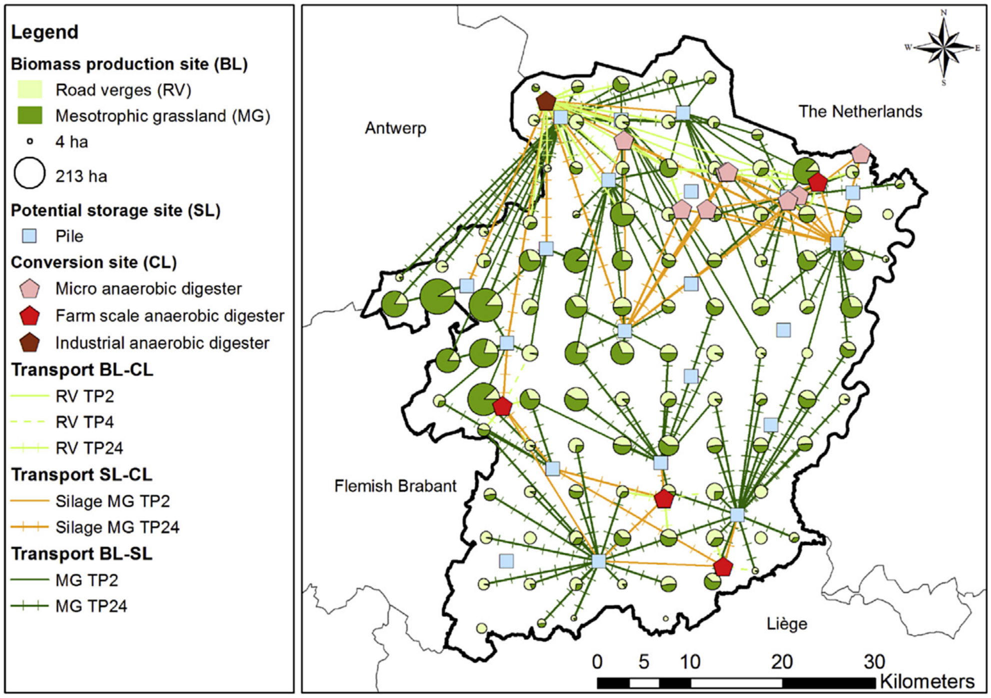

Fig. 6. Spatial layout of the supply of LIHD biomass to the existing wet anaerobic digesters in Limburg considering biomass growth and regeneration (Scenario 1A). – Presentation of all biomass flows throughout the one-year time horizon.

The biomass mixture converted in the anaerobic digesters consists of 80% pig slurry, 15% maize and 5% grass from nature reserves or road verges. The high quantity of pig slurry relates to the required high moisture content of the biomass mixture (between 80% and 95%) and the relatively low energy input to deliver pig slurry to the digester (Table C.1). In addition, t-OPTIMASS chooses to use maize in stead of organic household waste due to the higher biogas yield of maize (Table C.1). Not more grass from LIHD systems is used than the required 5%. This is mainly related to the high energy input for handling and transport of LIHD biomass (Table C.2) in comparison to the energy needed to deliver pig slurry and maize to the digester (i.e. energy input of extra products in table C.1). In the mixture of LIHD biomass, 83% consists of grass from mesotrophic grassland and only 17% of grass from road verges. The biomass from mesotrophic grasslands is harvested by rotary mower (as required) and stored in one of the 14 opened storage locations where it is ensilaged (Fig. 6). After chopping, this silage is converted to biogas (mainly) during the non-harvesting periods (TP1, TP3 and TP5) (Fig. 7). Analysis indicates that all available grass from mesotrophic grasslands is harvested in both TP2 and TP4. To meet the required 5% LIHD biomass in the conversion mixture, grass from road verges (harvested by flail mower) is added to the mixture only during harvesting periods because grass from road verges does not require ensilaging prior to digestion (Fig. 7).

Scenario 1A states that grass from mesotrophic grassland is more preferred than grass from road verges. This is mainly due to the fact that grass from mesotrophic grasslands does not need the energy intensive filtering operation (Table C.2). This conclusion is endorsed by the analysis of scenario 1B in which all LIHD biomass available in TP2 and TP4 must be harvested (Scenario 1B in Table 1). This forces the increase of LIHD in the conversion mixture from the minimum required 5% to 8.3%. The net energy output in scenario 1B decreases with ±4%, among others due to a tripling of the energy input related to filtering of the grass from road verges. So, to meet exactly the same gross energy output, the energy efficiency of the supply chain rises from 55% in the suboptimal scenario (Scenario 1B) to 58% in the optimal scenario (Scenario 1A).

4.2. Scenario 2: the potential of dry anaerobic digesters

Dry anaerobic digestion in Flanders is an exception [43]. Different studies point to the potential of dry anaerobic digesters for the digestion of grass in combination with organic household waste [43,47–51]. To evaluate the potential to process grass from LIHD systems in dry anaerobic digesters, in this scenario all wet anaerobic digesters (from scenario 1) are replaced by dry anaerobic digesters of the same capacity. The moisture

Table 1
Energy output (GJ), related energy inputs (GJ) and the total quantity of harvested and converted biomass (ton) in the LIHD-for-biogas supply chain optimised for the current network with wet anaerobic digesters without or with the requirement to use all LIHD biomass (resp. Scenario 1A and 1B) and considering potential dry anaerobic digesters (Scenario 2).

	Scenario 1A	Scenario 1B	Scenario 2	Unit
Gross energy output	525460	525478	525531	GJ
Energy input (LIHD):				
Transport	9484	13145	8633	GJ
Harvest	1482	2309	1774	GJ
Collection	4177	5170	3532	GJ
Pre-treatment	6479	18313	489	GJ
Storage	2494	2381	1050	GJ
Conversion	101117	101117	101117	GJ
Energy input (extra)	96249	90958	115093	GJ
Net energy output	303979	292084	293844	GJ
Quantity harvested biomass	20795	33921	26705	ton
Quantity converted biomass	18659	31265	25689	ton

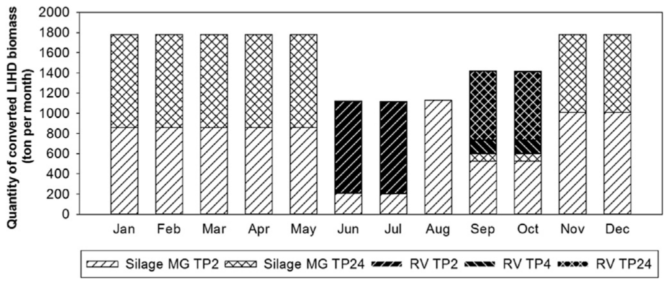

Fig. 7. Optimised monthly quantity of LIHD biomass products converted in the wet anaerobic digesters (Scenario 1A).

content of the biomass mixture in the digester must be between 60 and 80% and only maize and organic household waste are included as extra products [43]. By default, a dry digester for organic household waste is equipped with a pre-treatment to separate interfering substances such as litter, metal, etc. [43]. Therefore, the energy intensive filtering of grass from road verges prior to the feeding into the digester is not longer required [43]. In this supply chain, 220043 GJ of electricity and 305488 GJ of heat are produced. Around 44% of the total energy output is needed to perform all operations in the chain (Scenario 2 in Table 1).

The lower net energy output is directly related to the energy input to deliver organic household waste to the digester which is much higher than the energy input defined for pig slurry (Table C.1). After excluding the energy needed for usage of these extra products, it is clear that the dry anaerobic digesting results in a more efficient chain. The total quantity of LIHD biomass converted in the chain rises with 38% (Table 1) while the total energy input for LIHD usage drops with 36% (Table 1) mainly due to the unnecessity of the filter requirement. Grass from mesotrophic grasslands does not need to be chopped and can be digested without prior ensilaging. Also, LIHD biomass is mainly used in the period in which it is harvested reducing the energy related to the storage operations (only 5 out of 21 storages are opened) (Fig. 8).

While in scenario 1A, all mesotrophic grassland has been harvested and only 17% of the LIHD biomass emanates from road verges, this is reversed when using dry anaerobic digesters (with 63% from road verges and 37% from mesotrophic grassland) (Fig. 8). In comparison to scenario 1A, silage from mesotrophic grassland is transported over larger distances. This is mainly due to the fact that a fixed energy input is attributed to the opening of a storage facility. Therefore, the number of used storage facilities is minimised to store the needed silage.

Further analysis indicates that in the harvesting periods the use of biomass from the LIHD systems is more beneficial than using organic household waste (42% in TP2 and 23% in TP4) (Fig. 9). During the non-harvesting periods, its share is only the required 5% of the biomass mixture. This implies that more energy is needed to pre-treat and store the LIHD biomass compared to the energy input defined to deliver organic household waste to the digester (Table C.2).

5. Sensitivity analysis

5.1. Sensitivity to changes in harvestable biomass production

Uncertainty induced by among others weather conditions (e.g., long winter, early spring, long summer) can affect the available quantity of biomass during the allowed harvesting moments (TP2 and TP4). Considering scenario 1A, the effect of this uncertainty has been investigated by varying the harvestable biomass production (HBP_t^f) in TP2 (June/July) and subsequently in TP4 (September/October) between the lowest harvestable biomass production resulting in a feasible solution without changing constraints or other parameters and a doubling of the harvestable biomass production defined in table C.1.

Fig. 10 indicates that in both cases the net energy output increases when more LIHD biomass is available. Since the deviation in gross energy output is small due to the fixed demand constraint, this implies that the energy input in the chain decreases. This trend is more pronounced when the availability of biomass is limited (<100%). If less biomass is available in the first harvesting period (Fig. 10), the requirement of min 5% of the conversion mixture can be met with biomass harvested in the second harvesting period. In the first feasible solution (13% of the harvestable biomass production) all biomass available in both harvesting periods is harvested. The net energy output is small due to high energy need for extra products and long-term storage. In case of, for example, a late spring or short summer, less biomass is available in the second harvesting period (TP4). Therefore, almost all storage facilities are opened to store grass from nature reserves and road verges harvested in TP2 to meet the required biomass supply in the subsequent periods.

As the available biomass production increases, the share of grass from road verges decreases (from 26% (TP2) and 39% (TP4) to 0% in both cases) and more mesotrophic grass is harvested in TP2 and in TP4 to be stored as silage to guarantee year-round supply of biomass to the digester. Since the biogas production from mesotrophic grass is higher and the energy use for its pre-treatment is lower in comparison to grass from road verges (Tables C.1 and C.2), the share of silage from mesotrophic grassland harvested in harvesting period 1 rises to the detriment of grass from road verges. Although the quantity of ensilaged grass increases, the total energy related to pre-treatment in the chain decreases due to the high energy input for the filtering of grass from road verges. In the harvesting periods, grass from road verges is directly transported to the anaerobic digesters, while mesotrophic grass and the surplus of grass from road verges is ensilaged to be digested during the non-harvesting periods. The energy input related to the use of extra products also decreases since more LIHD biomass becomes available in the areas close to the anaerobic digesters. The net energy output reaches an equilibrium when more biomass is available (>100%). The main explanation is that the total maximum storage capacity is reached which limits the amount of silage to be produced and stored in the supply chain. The constraints defining the moisture content requirements in the conversion facility limit the amount of biomass allowed in the conversion process.

5.2. Sensitivity to energy input related to the use of extra product

The results of the scenarios point out that a large share of the energy input is related to the use of the (required) extra products (i.e. maize, organic household waste and pig slurry). Since an exact value for this energy input could not be found in literature and thus had to be estimated, this section investigates the effect of changes in the energy input related to the extra product. Therefore, the energy input defined in table C.1 has been multiplied with factors ranging between 0 and 15 (Fig. 11) based on scenario 1A. Although a factor of 15 is unrealistic, it has been included in the sensitivity analysis to investigate at which point the result reaches a steady state.

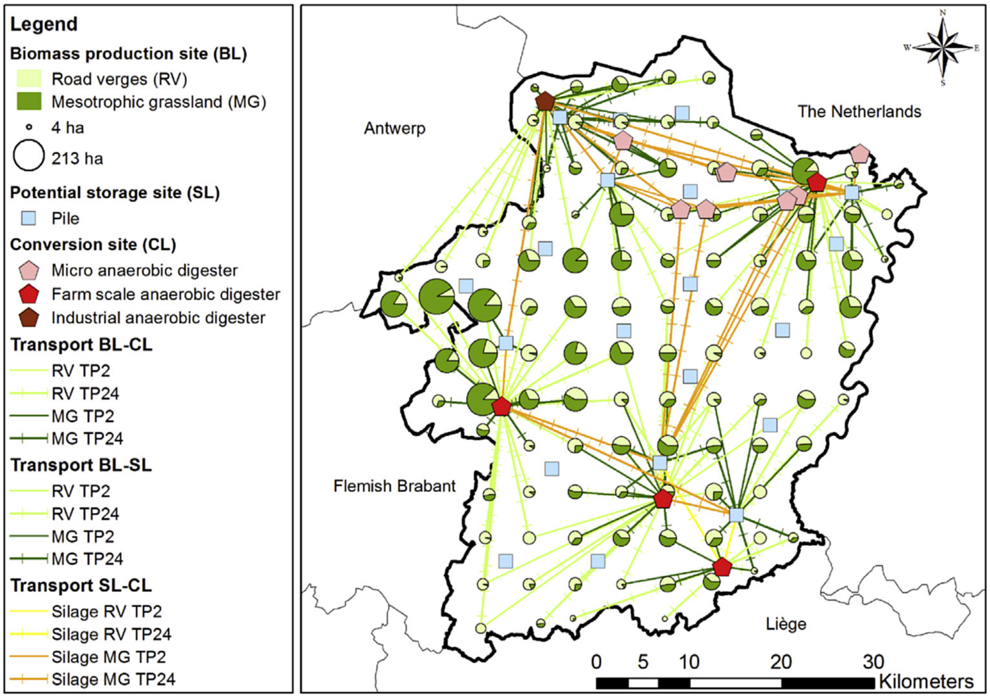

Fig. 8. Spatial layout of the LIHD-for-biogas supply chain considering potential dry anaerobic digesters in Limburg considering biomass growth and regeneration (Scenario 2) – Presentation of all biomass flows within the time horizon of 1 year.

Fig. 11 indicates that until a doubling of the energy input related to the extra products (A), the use of extra products is more beneficial than the use of LIHD biomass. The share of LIHD biomass in the conversion mixture of the anaerobic digesters only is at the minimum required 5%. Most LIHD biomass converted in the digesters originates from the mesotrophic grasslands and these areas are harvested in TP2 and TP4. The share of grass from road verges is small, but increases as the energy input for delivery of extra products increases. Also here, the quantity of grass from road verges is reduced due to the high energy input related to the required filtering treatment (Table C.2). From point (A), the share of LIHD biomass in the total conversion mixture rises until it reaches a steady state of 7.9% (B). This rise relates to the increase of grass from mesotrophic grasslands harvested for the second time (MG TP24). In addition, the share of grass from road verges harvested in the first harvesting period (TP2) grows. First, this grass is immediately converted in the anaerobic digester. However, reaching the steady state at point (B), most grass from road verges is being ensilaged. The main driver for this decision is the higher moisture content of silage in comparison to grass. After point (B), the biomass mixture remains unchanged.

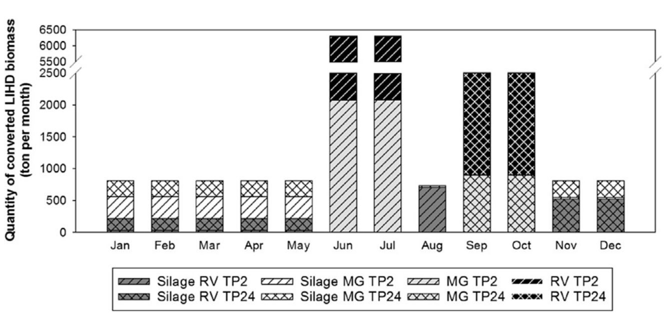

Fig. 9. Optimised monthly quantity of converted LIHD biomass converted in the potential dry anaerobic digesters (Scenario 2).

The analysis of the energy inputs needed for the different operations indicates that a steady increase is attributed to the harvest, collection, storage and transport of the LIHD biomass. This increase is directly related to the rising quantity of LIHD biomass used in the chain. However, the transition towards the use of grass from road verges and the increase of ensilaging mainly induces a much higher rise in the energy input related to the pre-treatment operations in the supply chain. This induces a decrease of the gross energy output from 526000 JG at point (A) to a steady state of ±506000 GJ at point (B).

In this case study, it has been stated that the share of pig slurry in the conversion mixture of wet anaerobic digesters must range between 50% and 80% mainly to meet the high moisture content requirement at the digester. This sensitivity analysis highlights that the optimal result depends on the energy input needed to deliver the extra products to the digesters. This indicates that results will differ when other processes, with other energy inputs, are included to reach the high moisture content requirement, such as recirculation of liquid digester, addition of water, etc. New scenarios can be run using these processes and their related energy input to investigate the impact on the optimised supply chain.

6. Discussion

The decision process is strongly driven by the requirements (moisture content, particle size, etc.) of the conversion facilities. The feeding rate defines the minimum required and maximum allowed quantity of biomass that can be processed by the conversion facilities and this has a clear influence on the allocation pattern. The regulation of biomass mixture to be converted at the facility defines what kind of biomass is delivered to the conversion facility. The moisture content and particle size requirements define in which format the biomass must be delivered. These requirements impose the need to include

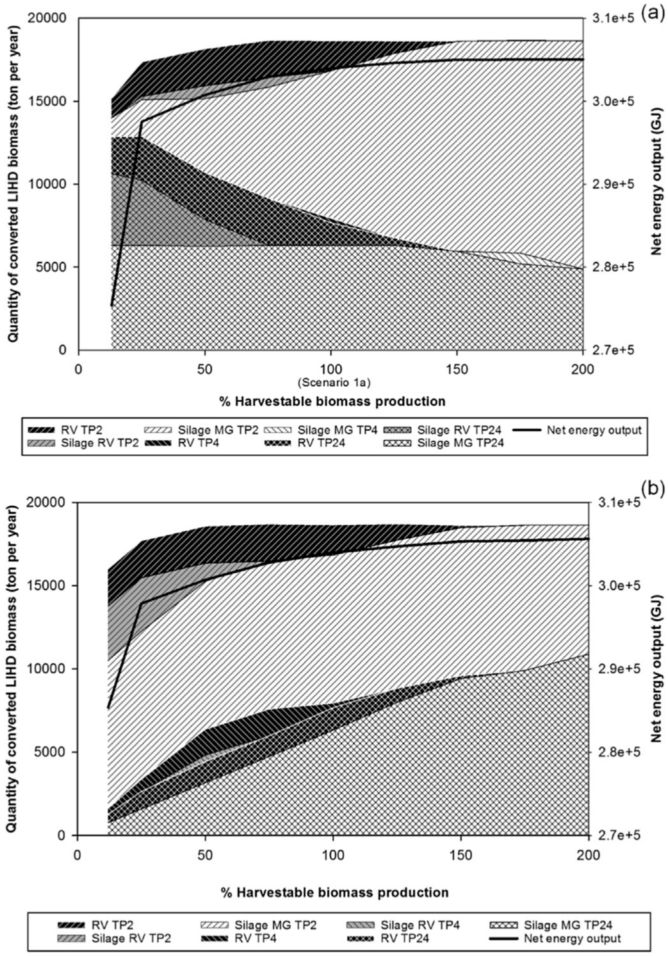

Fig. 10. Sensitivity of the quantity and type of LIHD biomass converted in the wet anaerobic digesters and of the net energy output to changes in harvestable biomass production in (a) the first harvesting period (TP2) and (b) the second harvesting period (TP4).

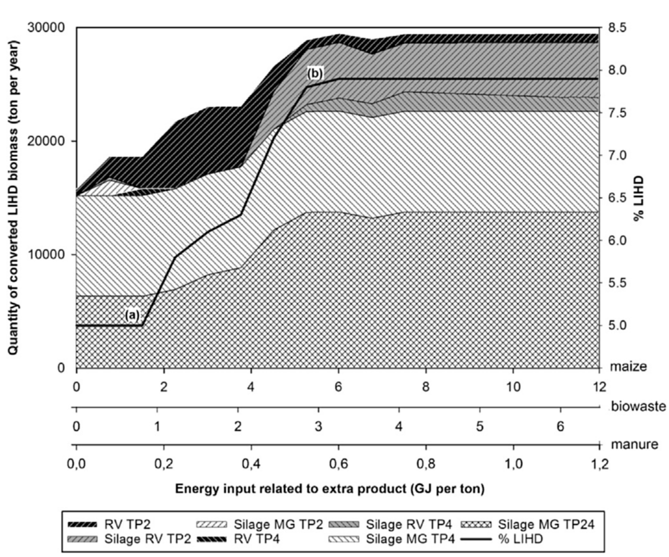

Fig. 11. Sensitivity of the quantity and type of LIHD biomass converted in the wet anaerobic digesters and the share of LIHD in the converted mixture to the energy input related to the use of the extra products (maize, biowaste and manure).

changes in biomass characteristics due to handling operations and the growth stage at the moment of harvesting. In addition, the analyses state that it is more beneficial to use biomass with characteristics that fit the requirements of the conversion facilities or to introduce conversion facilities with requirements that fit the characteristics of the available biomass. This reduces the cost for pre-treatment operations and an overload of storage needs.

The scenario and sensitivity analyses based in the LIHD-to-biogas supply chain indicate that storage facilities are indispensable to deal with the temporal availability of biomass, the conflicting temporal energy demand and the required constant feeding of the conversion facilities. In this case study, the storage sites are assumed to be on the most likely locations in Limburg and a capacity of 1500 m^3 is pre-defined due to a lack of real-world data. A sensitivity analysis of the storage capacity points out that a capacity of at least 705 m^3 is needed in the 21 storage locations to make the supply chain feasible. From a capacity of 1875 m^3 the result reaches a steady state with the gradual opening of 13 storage locations. Furthermore, the sensitivity analysis indicates that the higher the available storage capacity, the more LIHD biomass is used in the supply chain. It is obvious that the choice of the potential storage locations prior to optimisation will have an impact on the result since the biomass network changes. Introducing more potential storage locations and performing a thorough spatial analysis based on multi-criteria decision analysis to define the potential sites will allow t-OPTIMASS to determine the best sites and indicate the locations that turn out to be unprofitable.

Because t-OPTIMASS optimises the supply chain across all areas, all processes and over the entire time horizon, inter-temporal processes might influence the decision making. However, these inter-temporal processes are not considered in t-OPTIMASS. While this is acceptable in the context of maximising the net energy output as applied in this manuscript, it is necessary to consider intertemporal discounting when evaluating the economic objective. Therefore, future research opportunities point to the extension of t-OPTIMASS with approaches such as dynamic optimization employing rational expectations or recursive optimization linked to stochastic processes.

t-OPTIMASS considers product loss during storage as a fixed fraction of biomass and defines a specified biogas reduction (8%) due to ensilaging independent of the storage duration. However, these values are fixed and are independent of the length of the storage period. To improve the decisions considering storage duration and sustainable use of biomass, deteriorating inventory models can be included in t-OPTIMASS. Also, a temporal capacity of extra products can be easily added to t-OPTIMASS to include the use of multiple products available in different periods. Furthermore, t-OPTIMASS, as described in this paper, assumes a steady state regime (Equation (5a) and (6a)) which implies that the harvestable biomass production and energy demand change according to the same seasonal pattern every year. To consider influence of e.g. climate change in decision making, t-OPTIMASS can be extended to consider this effect on these patterns. However, due to the complexity of the model and the large number of integer variables (among others due to the incorporation of pre-treatment operations), computation times can increase significantly. This requires a trade-off between making the model more realistic and the tolerated computational time.

The analysis of the current situation (Scenario 1) highlights that the share of LIHD biomass in the conversion mixture is limited to the minimum required 5%. Analysis has pointed out that this limitation relates directly to the estimated energy input needed to use the extra products (Section 5.2). To make a well-founded statement about the value of LIHD biomass in bioenergy production, analysis with more reliable, quantitative values addressing the energy input (especially related to the use of extra products) is needed. In this paper the main goal is to illustrate the potential of t-OPTIMASS. The results indicate a direction of change, but do not intend to present the most realistic values. Section 5.2 indicates that a small energy input related to extra products stimulates the use of LIHD biomass.

7. Conclusion

This paper presents the expansion of OPTIMASS towards a multi-period mixed integer linear programming model, t-OPTIMASS, to optimise strategic and tactical decisions in all kinds of biomass supply chains based on the maximal net energy output. The model takes into account the main characteristics of the biomass supply chain, i.e. geographical fragmentation and availability of biomass resources, growth and regeneration of biomass, seasonal energy demand, changing biomass characteristics due to handling operations and growth. Unlike existing multi-period models, t-OPTIMASS considers the temporal cyclicity or regeneration in the production of biomass to determine the optimal harvesting moment(s) throughout the time horizon considering the changing energy demand and the requirement of continuous supply of biomass to the digesters. By the incorporation of changes in biomass characteristics due to handling operations and the growth and regeneration of biomass in the decision process, t-OPTIMASS is able to optimise the supply chain ensuring the sustainable use of biomass which becomes decisive when modern bioenergy supply scales up significantly. The generic approach enables the applicability of t-OPTIMASS to all kinds of biomass supply chains. This is illustrated by its application to the supply chain of poplar wood to saw mills and paper mills in Belgium. In this case, the constant supply of poplar must balance the accretion in the field considering the growth of poplar, a minimum required regeneration period and a time horizon of 30 year. Besides dealing with annual and perennial crops, t-OPTIMASS can also be applied to optimise the supply chain of biomass with seasonal availability of biomass but lacking growth and regeneration. This is studied in an on-going case study in which the supply of organic household waste to a composting facility in Belgium is optimised and another case study in which the processing chain of sludge from municipal wastewater treatment plants is studied [52].

In general, the results highlight that the use of multiple products enables the use of each biomass type in a more optimal way and moment. The requirements imposed to the biomass mixture at the conversion facilities are the main drivers in the decision process. So, the harvesting moment is defined and treatment operations are introduced to make sure that biomass is delivered with characteristics that fit best these requirements. In addition, the analyses indicate that storage facilities are indispensable to deal with the temporal availability of biomass, the conflicting temporal (energy) demand and the required constant feeding of the conversion facilities. This implies that, besides the definition of the optimal location and type of conversion facilities, the optimisation of the location and type of storage facilities is a decisive factor in the design of a sustainable biomass network.

We believe that the generator prototype is an inspiring tool for a variety of stakeholders working with or having a large impact on the biomass sector and mostly interested in a macro-analysis (e.g., governments, government institutions, consultancy agents, etc.). Stakeholders are able to get insight in evolutions of biomass flows and the development of the biomass network through the simulation of the consequences of e.g. political decisions, import restrictions, introducing toll, etc. This way the output contributes to the formulation of new biomass-related policies and implementation rules. The tool supports the evaluation of the biomass potential, the feasibility of new operation facilities and the definition of the optimal type and location of facilities out of the potential facilities proposed by the user. A range of scenarios can be run serving as the basis for a dialogue between the various stakeholders working with biomass to help resolve bottlenecks hampering the optimal use of biomass. Also guidance can be provided to stakeholders (e.g., biomass suppliers, owners and operators of storage and conversion facilities) ones the biomass network is designed to evaluate the impact of e.g., the shortage in biomass supply, bankruptcy of a neighbouring operation facility, potential new biomass sites, etc.

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Appendix A. List of abbreviations

CHP	Combined heat and power installation
FAD	Farm scale anaerobic digester
IAD	Industrial anaerobic digester
LIHD	Low input high diversity
MAD	Micro anaerobic digester
MILP	Mixed integer linear programming model
TP	Time period

Appendix B. List of symbols

Appendix B.1. Indices

c	conversion type
f	product type
h	harvesting type
i	location of biomass production site
j	potential location to install a storage facility
k	potential location to install a conversion facility
o	bioenergy output type
p	pre-treatment type
r	product type
s	storage type
t	time period

Appendix B.2. Parameters

$AREA_i^f$	Area of product type f at biomass production site i (ha)
CV^{biogas}	Calorific value of biogas (assumed to be 6 kWh m^{-3})
D_t^o	Demand for bioenergy of type o in time period t (GJ)
HBP^f	Harvestable biomass production of product type f (ton ha^{-1})
Q^o	Coefficient to define the allowed energy surplus as a function of the energy demand (%)
γ_H^{fr}	Transformation coefficient defining the change in product type due to harvest (%)
γ_{NH}^{fr}	Transformation coefficient defining the change in product type due to growth (non harvest) (%)
Δ^s	Product loss during storage type s (%)
η^{co}	Conversion efficiency of conversion technology c for bioenergy production of type o (%)
ρ^f	Biogas yield of product type f ($m^3\ t^{-1}$)
ρ^e	Biogas yield of extra product of type f ($m^3\ t^{-1}$)

Appendix B.3. Decision variables

C^{fk}_{ct}	Quantity of product type f converted in the conversion facility with conversion technology c at location k in time period t (ton)
E^{co}_{kt}	Quantity of bioenergy of type o produced at conversion facility with technology c at location k (GJ)
$E^{o}_{surplust}$	Total quantity of surplus energy of type o generated in the supply chain in time period t (GJ)
I^{fk}_{ct}	Inventory of product type f at conversion location k of conversion type c in time period t (ton)
I^{fs}_{jt}	Inventory of product type f at storage location j of storage type s in time period t (ton)
P^{spf}_{jt}	Quantity of product type f produced after pre-treatment p at storage facility with storage type s at location j in time period t (ton)
P^{cpf}_{kt}	Quantity of product type f produced after pre-treatment p at conversion facility with conversion type c at location k in time period t (ton)
sH^{f}_{it}	Sum of product type f harvested at biomass production site i in time period t(ton)
sNH^{f}_{it}	Sum of product type f not harvested at biomass production site i in time period t (ton)
$SUPmax^{f}_{it}$	Maximum quantity of biomass of type f available at biomass production site i in time period t (ton)
UX^{ec}_{kt}	Quantity of extra product of type e converted in the conversion facility with conversion technology c at location k in time period t (ton)
U^{fc}_{kt}	Quantity of product type f converted in the conversion facility with conversion technology c at location k in time period t (ton)
X^{fk}_{ct}	Quantity of product type f delivered at the conversion facility with conversion technology c at location k in time period t (ton)
X^{fk}_{cpt}	Quantity of product type f pre-treated by pre-treatment type p at the conversion facility with conversion technology c at location k in time period t (ton)
X^{fs}_{injt}	Quantity of product type f delivered at the storage facility of storage type s at location j in time period t (ton)
X^{fsp}_{injt}	Quantity of product type f delivered at pre-treatment type p at the storage facility of storage type s at location j in time period t (ton)
X^{fs}_{outjt}	Quantity of product type f leaving storage facility of storage type s at location j in time period t (ton)

Appendix C. Parameters used in the case study

Table C.1
Attributes and their values describing the LIHD product types (MC = Mowing cycle, ODS = dry matter fraction of organic dry solids, DS = dry solids, RV = grass from road verges, MG = grass from mesotrophic grassland, TP2 = harvest in time period 2, TP4 = harvest in time period 4, TP24 = harvest in time period 2 as well as time period 4)

Product type	Biomass yield (t $ha^{-1}MC^{-1}$)	Biogas yield (m^3 t^{-1})	Biomass water content (% of fresh weight)	ODS (% DS)	Particle size (mm)
RV – TP2	4.3[c]	100[c]	70[c]		20[c]
RV – TP4	3.6[c]	50[c]	70[c]		20[c]
RV – TP24	3.2[c]	100[c]	70[c]		20[c]
MG – TP2	3.8[a]	120[b]	65[a]	91[a]	52[a]
MG – TP4	3.2[a]	60[b]	65[a]	91[a]	40[a]
MG – TP24	2.7[a]	120[b]	65[a]	91[a]	35[a]
Silage RV – TP2	–	92[d]	72[e]		20[e]
Silage RV – TP4	–	46[d]	72[e]		20[e]
Silage RV – TP24	–	92[d]	72[e]		20[e]
Silage MG – TP2	–	110[d]	72[e]		52[e]
Silage MG – TP4	–	55[d]	72[e]		40[e]
Silage MG – TP24	–	110[d]	72[e]		35[e]
Chopped silage MG – TP2	–	110[d]	72[e]		12[e]
Chopped silage MG – TP4	–	55[d]	72[e]		12[e]
Chopped silage MG – TP24	–	110[d]	72[e]		12[e]

Extra product type	Energy input for supply (GJ t^{-1})	Biogas yield (m^3 t^{-1})	Biomass water content (% of fresh weight)
Maize	0.25[j]	170[d]	71[f]
Organic household waste	0.1815[j]	100[g]	73[g]
Pig slurry	0.1696[j]	20[i]	91[h]

References.
[a] Based on [39].
[b] [40].
[c] Based on [54].
[d] [56].
[e] [48].
[f] [29].
[g] [53].
[h] [55].
[i] [57].
[j] [58].

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Table C.2
Attributes and their values describing the operation types in the LIHD supply chain.

HARVEST	Operation	Management	Capacity	Speed	Width
Rotary mower	0.295 GJ h^{-1} [a]	0.0014 GJ km^{-1} [b]	100 t $month^{-1}$ [c]	8.3 km h^{-1} [d]	1.52 m [d]
Flail mower	0.236 GJ h^{-1} [a]	0.0019 GJ km^{-1} [b]	100 t $month^{-1}$ [c]	5.8 km h^{-1} [e]	1.72 m [e]

COLLECTION	Operation	Management	Capacity	Product loss
Tractor with trailer	0.227 GJ t^{-1} [f]	0.0092 GJ km^{-1} [b]	680 t $month^{-1}$ [g]	2% [i]
Mow-load combination	0.076 GJ t^{-1} [f]	0.0031 GJ km^{-1} [b]	227 t $month^{-1}$ [h]	2% [i]

PRE-TREATMENT	Operation	Management	Capacity	Product loss
Filtering	0.92 GJ t^{-1} [j,k]	350.0 GJ $month^{-1}$ [j,k]	5000 t $month^{-1}$ [j,k]	2% [i]
Ensilaging	0.07 GJ t^{-1} [f]	98.8 GJ $month^{-1}$ [a]	2917 t $month^{-1}$ [k]	7% [i]
Chopping	0.13 GJ t^{-1} [i]	225.0 GJ $month^{-1}$ [a]	500 t $month^{-1}$ [a]	3% [i]

STORAGE	Management	Capacity	Product loss
Pile	6.25 GJ $month^{-1}$ [a]	1500 m^3 $month^{-1}$	2% [i]

CONVERSION	Management	Feeding rate	Electric capacity	Efficiency	Moisture content	Particle size
Micro scale anaerobic digester	39.3 GJ $month^{-1}$ [l]	54 − 417 t $month^{-1}$ [l]	20 MWh^{el} $month^{-1}$ [l]	32% (el)/58% (th) [l]	80 − 95% [k]	5–20 mm [k]
Farm scale anaerobic digester	1008 GJ $month^{-1}$ [m]	1667 − 6667 t $month^{-1}$ [n]	667 MWh^{el} $month^{-1}$ [n]	34% (el)/47% (th) [o]	80 − 95% [k]	5–20 mm [k]
Industrial anaerobic digester	4080 GJ $month^{-1}$ [m]	7500 − 25000 t $month^{-1}$ [p]	3833 MWh^{el} $month^{-1}$ [p]	38% (el)/52% (th) [p]	80 − 95% [k]	5–20 mm [k]

TRANSPORT	Transport	Load	Unload
Truck	0.0014 GJ t^{-1} km^{-1} [q]	0.1545 GJ t^{-1} [f]	0.1996 GJ t^{-1} [f]
Tractor	0.0029 GJ t^{-1} km^{-1} [q]	0.227 GJ t^{-1} [f]	0.005 GJ t^{-1} [f]

References.
[a] [41].
[b] Based on [60].
[c] Calculated using HBP^f, ρ^f, v^h, w^h and a load factor of 125 h $month^{-1}$.
[d] [62].
[e] [64].
[f] [65].
[g] [67].
[h] [69].
[i] Based on [59].
[j] Based on [61].
[k] Based on [48].
[l] Based on [63].
[m] Based on [53].
[n] Based on [66].
[o] [68].
[p] [70].
[q] [71].

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