A MIXED INTEGER LINEAR PROGRAMMING MODEL FOR THE STRATEGIC OPTIMISATION OF BIOMASS-FOR-BIOENERGY SUPPLY CHAINS

A. De Meyer [1], D. Cattrysse[2], J. Van Orshoven[1]
[1] Department of Earth & Environmental Sciences, KU Leuven, Celestijnenlaan 200E, 3001 Leuven, Belgium
[2] Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300A, 3001 Leuven, Belgium

ABSTRACT: This paper addresses the strategic design of the biomass-for-bioenergy (B4B) supply chain with a view to optimise energetic, economical or environmental criteria. This B4B supply chain consists of six key operations: biomass production, harvest, collection, pre-treatment, storage and conversion to bioenergy. All these operations occur at biomass production sites or in facilities connected through transport and transhipment infrastructure. In contrast with other optimisation models, the proposed mixed integer linear programming (MILP) model considers supply chain restrictions, available transportation networks and corresponding interrelationships and interdependencies between operations. The optimisation model selects the optimal location, technology and capacity of storage, pre-treatment and conversion facilities. Simultaneously, the optimal allocation of raw biomass, intermediate products and by-products from production sites to operation facilities and between facilities are defined. The MILP includes three objective functions: (1) maximise total energy output, (2) maximise overall profit and (3) minimise greenhouse gas emissions. The functionalities of the proposed MILP are illustrated by means of a simplified B4B supply chain based on grass and brushwood from low input high diversity biomass systems in the province of Limburg (Belgium). Analysis of the different scenarios confirms the response capacity of the MILP to change in information.
Keywords: biomass, supply chain, modelling, strategy.

1 INTRODUCTION

The consequences of climate change, the rising awareness of the finiteness of fossil fuels and the increase of energy consumption strengthen the importance of alternative and renewable energy sources on the agenda of public and private institutions. For example, the targets set by the member states of the European Union (EU) in the “Climate Action and Renewable Energy Package” to become a highly energy efficient, low carbon economy by 2020 [1]. Bioenergy is high on the list of options for addressing these targets [2–4] because biomass is a very versatile energy source and it is one of the few renewable energy sources that may be stored and can be converted to energy on-demand [5]. However, a well-developed B4B network is required to ensure that energy from biomass is economically, environmentally and socially sustainable. In this context, the bioenergy network is usually divided in three major supply chain segments: (1) the upstream segment covering the operations from biomass production to conversion to bioenergy, (2) the midstream segment considering the conversion process itself and (3) the downstream segment encompassing the storage of bioenergy and its distribution to the customers [6] (Figure 1).

One of the most important barriers hampering the development of a strong bioenergy sector is the cost of the (upstream) biomass-for-bioenergy (B4B) supply chain [5] because handling and transport of biomass from the source location to the conversion facility induce a variety of economic, energetic and environmental implications [4]. Handling of biomass requires a sequence of operations to deal with the typical characteristics of biomass like spatial fragmentation, seasonal and weather related variability, high moisture content, low energy content and low bulk density [5], [7–10]. Six key operations can be distinguished; i.e. biomass production, harvest, collection, pre-treatment, storage and conversion to bioenergy (Figure 1) [11]. Since the conversion process is part of the midstream segment, in this paper the conversion to bioenergy is considered as a black box with input of biomass and output of bioenergy and by-products. All these operations occur at biomass production sites or in operation facilities connected through transport and transhipment infrastructure. The interrelationships and interdependencies between operations complicate the supply chain in the sense that upstream decisions affect the later operations in the chain. Moreover, the choice of the biomass conversion technology, its size and location co-determine the type and sequence of all previous operations. In addition, biomass supply chains need to be robust and flexible to allow adaptation to weather related availability of biomass, competing usage and perishability of biomass and unpredictable changes in market conditions [9].

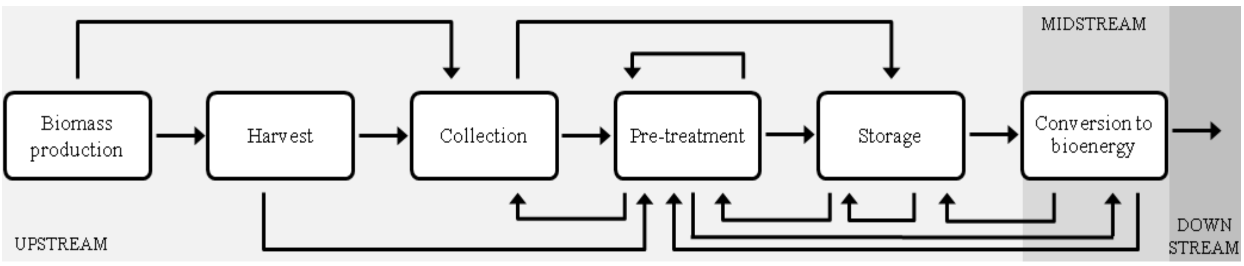

Figure 1 Flow chart representing the sequence of operations in the biomass supply chain [11]

Besides the barriers mentioned above, uncertainties regarding the biomass supply, transportation, logistics, production, operation, demand and price hamper the performance of the bioenergy sector [12]. It can be anticipated that the role that bioenergy will play in the future 'global energy mix' will depend upon the extent to which the barriers or uncertainties inhibiting the development and international trade as well as a sustainable and efficient production of biomass resources and bioenergy can be overcome [13].

Since the major barriers and uncertainties relate to the upstream biomass supply chain and since the existence and competitiveness of the bioenergy industry depend on strategic plans for facility location, transportation infrastructure and biomass logistics [14], several authors introduce mathematical programming models (e.g. [15], [16]), heuristics (e.g. [17], [18]) and multiattribute decision analysis (e.g. [19], [20]) in the B4B research field. A review of the existing optimisation models has pointed out that the models are usually developed for specific cases addressing a specific part of the supply chain only, considering specific operations at one certain hierarchical decision level and incorporating far from all interrelationships and interdependencies between the operations considered in the supply chain [21]. Studies state that heuristics are generally used for operational problems which have to be solved rapidly, whereas mathematical programming methods are better for tactical and strategic planning problems which can be solved over a longer period of time (e.g. hours or even days) [22].

The mathematical programming model described in this paper focuses on the strategic optimisation of the complete upstream segment of the bioenergy supply chain. This implies the selection of the optimal location, technology and capacity of storage, pre-treatment and conversion facilities. Simultaneously, the allocation of raw biomass materials, intermediate products and by-products from production sites to these operation facilities and between operation facilities are defined. The goal of the proposed model is to account for supply chain restrictions, the available multimodal transportation network and the corresponding interrelationships and interdependencies between all operations. Furthermore, the MILP is meant to be applicable for all kinds of B4B supply chains. To confirm these possibilities and functionalities, this paper describes the basic structure of the MILP model and presents its application to a simplified B4B supply chain based on biomass from low input high diversity (LIHD) systems in the province of Limburg (Belgium).

2 OVERVIEW OF THE SPATIAL MILP MODEL

The proposed mathematical programming model is formulated as a mixed integer linear programming (MILP) model. The model optimises simultaneously:

- the location, technology and capacity of storage facilities;
- the location, technology and capacity of conversion facilities;
- the allocation of raw biomass materials, intermediate products and by-products from biomass production sites to operation facilities and between operation facilities;
- the type of harvesting and collection operations at the biomass production sites;
- the type of pre-treatment operations at biomass production sites, storage facilities and/or conversion facilities.

The problem is approached as a transhipment problem in which nodes correspond to biomass production sites, storage sites, and conversion sites while lines correspond to the product flow and transport operations [23–25]. Biomass production sites are represented by the supply nodes where harvesting, collection and pre-treatment operations (can) occur. The storage sites correspond to transhipment nodes where raw materials, intermediate products and by-products can be stored and/or pre-treated. Conversion sites match with demand points where pre-treatment, storage and conversion operations are performed. In addition, after conversion the by-products can re-enter the supply chain for further conversion to bio-energy or for alternative use (e.g. soil fertiliser). A schematic representation of the transhipment problem is shown in figure 2.

2.1 Decision variables

In a MILP model decision variables can be binary, integers or continuous while the objective function and all constraints are linear. In the proposed MILP, the continuous variables define:

- the quantities of raw biomass products harvested at the biomass production sites;
- the quantities of raw biomass products and intermediate products pre-treated and collected at the biomass production sites;
- the quantities of raw biomass materials and intermediate products transported from biomass production sites to storage and/or conversion facilities;
- the quantities of raw biomass products, intermediate products and by-products stored and/or pre-treated at the storage facilities;
- the quantities of raw biomass products, intermediate products and by-products pre-treated and converted at the conversion facilities;
- the quantities of by-products produced at conversion facilities;
- the quantities of intermediate products and by-products between storage and conversion facilities.

Integer variables indicate whether or not a specified harvesting and collection operation is performed at the biomass production site. If a harvesting or collection operation is applied, this variable indicates the number of units required to perform the operation.

Binary variables determine whether or not a storage or conversion facility with specified type and capacity is opened at the location, and whether or not a pre-treatment operation is performed at the biomass production site, a storage facility and/or a conversion facility.

2.2 Objective functions

The MILP includes an economic objective, an energetic objective and an environmental objective. Each of these objectives can be optimised individually. However, when the biomass supply chain is optimised for one objective, the value for the other objectives is also calculated. Optimisation based on multiple objectives will be possible in the near future, but is not yet included in the MILP model presented in this paper.

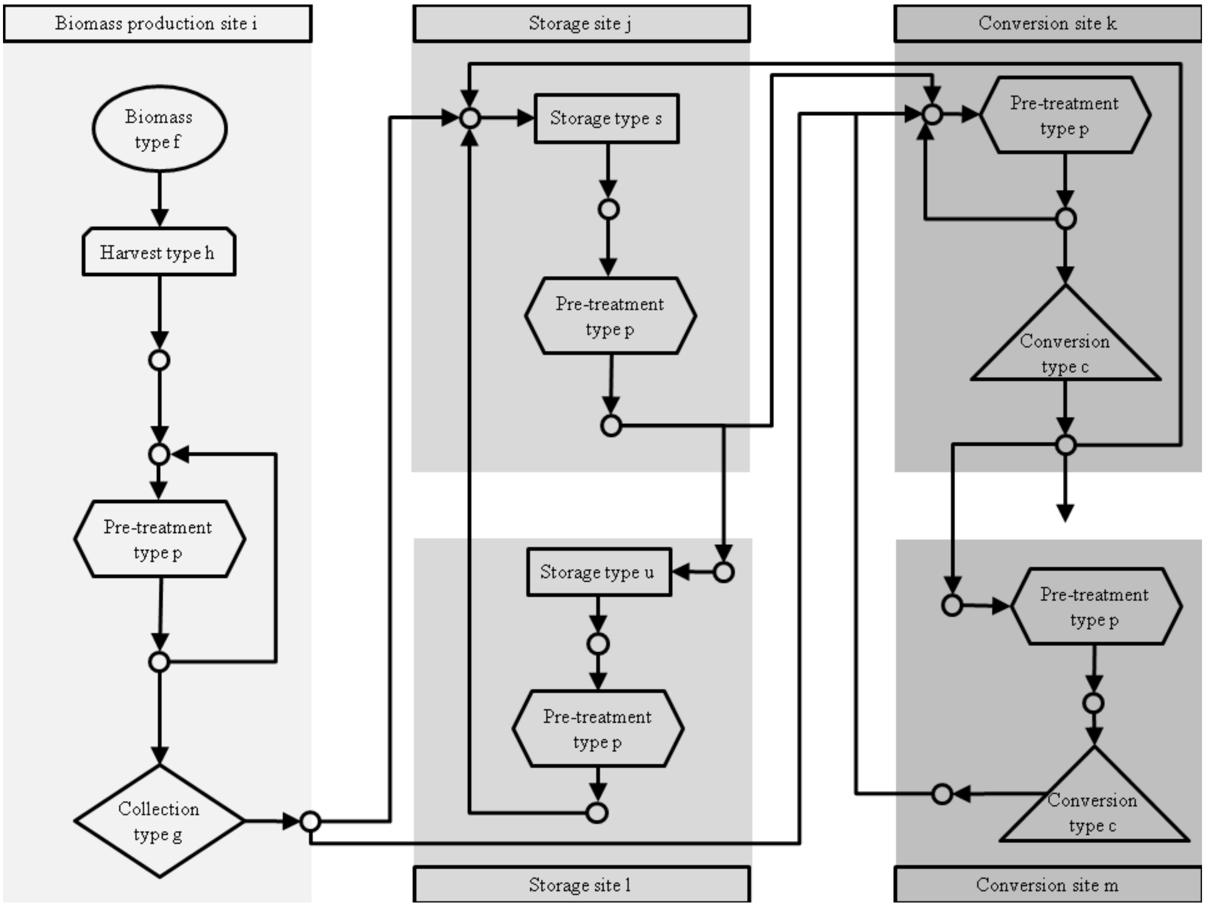

Figure 2 Schematic representation of the decision stages in the biomass-for-bioenergy supply chain according to the transhipment model

The **economic objective** maximises the annualised total profit of the B4B supply chain (PROFIT) (Eq. 1). The revenue of the total supply chain (INC) is determined by the energy price (P^o_{price}) and the governmental support (P^o_{cert}) (Eq. 2). The total cost is defined by the operation cost and the management cost (P_{in}^{start}) (Eq. 8). The operation cost includes the costs for harvesting the biomass (P^h_{in}) (Eq. 3), costs for collection and local transport (P^g_{in}) (Eq. 4), costs for pre-treatment operations (P^p_{in}) (Eq. 5) and costs for transport of raw materials, intermediate products and by-products (P^{tr}_{in}) (Eq. 6). The management cost is determined by the costs to run the facilities and the maintenance costs of the harvesting and collection equipment (Eq. 8).

$$\max PROFIT = INC - \left(P_{in}^h + P_{in}^g + P_{in}^p + P_{in}^{tr} + P_{in}^{start}\right) \qquad \text{Eq. 1}$$

With:
PROFIT = annualised total profit (€ y^{-1})
INC= annualised revenue (€ y^{-1})
P^h_{in} = total cost to harvest the biomass (€ y^{-1})
P^g_{in} = total cost to collect and for local transport (€ y^{-1})
P^p_{in} = total cost for pre-treatment operations (€ y^{-1})
P^{tr}_{in} = total cost for transportation (€ y^{-1})
P_{in}^{start} = total management cost (€ y^{-1})

$$INC = \sum_k \sum_c \sum_o \left[E_k^{co} \cdot \left(P_{price}^o + P_{cert}^o\right)\right] \qquad \text{Eq. 2}$$

With:
INC = revenue of the total supply chain (€ y^{-1})
E_k^{co} = amount of bioenergy of type o produced at conversion facility of conversion type c at location k (MWh y^{-1})
P^o_{price} = energy price (€ MWh^{-1})
P^o_{cert} = governmental support (€ MWh^{-1})

$$P_{in}^h = \sum_i \sum_f \sum_h \left[\frac{P^h \cdot X_i^{fh}}{10 \cdot v^h \cdot w^h \cdot HBP^f}\right] \qquad \text{Eq. 3}$$

With:
P^h_{in} = total cost to harvest the biomass (€ y^{-1})
P^h = cost for a harvesting operation with harvesting type h (€ h^{-1})
X_i^{fh} = amount of product type f harvested by harvesting type h at biomass production site i (Mg y^{-1})
v^h = harvesting speed of harvesting type h (km h^{-1})
w^h = harvesting width of harvesting type h (m)
HBP^f = harvestable biomass production of biomass type f(Mg ha^{-1} y^{-1})

$$P_{in}^g = \sum_i \sum_f \sum_g \left(d_i \cdot X_i^{fg} \cdot P^g\right) \qquad \text{Eq. 4}$$

With:
P^g_{in} = total cost to collect and for local transport (€ y^{-1})
d^i = bird fly distance from biomass production site i to nearest road (km)
X_i^{fg} = amount of product type f collected with collection type g at production site i (Mg y^{-1})
P^g = cost for a collection operation with collection type g (€ t^{-1} km^{-1})

$$P_{in}^p = \sum_i \sum_f \sum_p \left(X_i^{fp} \cdot P^p\right) + \sum_f \sum_j \sum_s \sum_p \left(W_{in\,j}^{fsp} \cdot P^p\right) + \sum_f \sum_k \sum_c \sum_p \left(V_k^{fcp} \cdot P^p\right) \qquad \text{Eq. 5}$$

With:
P^p_{in} = total cost for pre-treatment operations (€ y^{-1})
X_i^{fp} = amount of product type f pre-treated by pre-treatment type p at biomass production site i (Mg y^{-1})
$W^{fsp}_{in\,j}$ = amount of product type f pre-treated by pre-treatment type p at a storage facility of type s at location j (Mg y^{-1})
V_k^{fcp} = amount of product type f pre-treated by pre-treatment type p at conversion facility of type c at location k (Mg y^{-1})
P^p = cost to pre-treat products by pre-treatment type p (€ Mg^{-1})

$$P_{in}^{tr} = P_{ij} + P_{ik} + P_{jk} + P_{jl} + P_{kj} + P_{km} \quad \text{Eq. 6}$$

With:
P_{in}^{tr} = total cost for transportation (€ y^{-1})
P_{ij} = total cost for transport between biomass production sites and storage sites (€ y^{-1}) (Eq. 7)
P_{ik} = total cost for transport between biomass production sites and conversion sites (€ y^{-1}) (cf. Eq. 7)
P_{jk} = total cost for transport between storage sites and conversion sites (€ y^{-1}) (cf. Eq. 7)
P_{jl} = total cost for transport between storage sites mutually (€ y^{-1}) (cf. Eq. 7)
P_{kj} = total cost for transport between conversion sites and storage sites (€ y^{-1}) (cf. Eq. 7)
P_{km}= total cost for transport between conversion sites mutually (€ y^{-1}) (cf. Eq. 7)

$$P_{ij} = \sum_i \sum_f \sum_j \sum_s \sum_z \left[\left(d_{ij}^z \cdot X_{ij}^{fsz} \cdot P_{tr}^z \right) + \left(X_{ij}^{fsz} \cdot \left(P_{load}^z + P_{unload}^z \right) \right) \right] \quad \text{Eq. 7}$$

With:
P_{ij} = total cost for transport between biomass production sites and storage sites (€ y^{-1})
d^z_{ij} = shortest distance to transport products between biomass production site i and storage site j by transport type z (km)
X_{ij}^{fsz} = amount of product type f transported by transport type z from the biomass production site at location i to storage facility of type s at location j (Mg y^{-1})
P^z_{tr} = cost for transportation by transport type z (€ Mg^{-1} km^{-1})
P^z_{load} = cost to load transport type z (€ Mg^{-1})
P^z_{unload} = cost to unload transport type z (€ Mg^{-1})

$$P_{in}^{start} = \sum_i \sum_f \sum_h \left(Y_i^{fh} \cdot P_{man}^h \right) + \sum_i \sum_f \sum_g \left(Y_i^{fg} \cdot P_{man}^g \right) + \sum_i \sum_f \sum_p \left(Y_i^{fp} \cdot P_{man}^p \right) + \sum_j \sum_s \left(Y_j^s \cdot P_{man}^s \right) + \sum_k \sum_c \left(Y_k^c \cdot P_{man}^c \right) \quad \text{Eq. 8}$$

With:
P_{in}^{start} = total management cost (€ y^{-1})
Y_i^{fh} = integer variable indicating whether or not harvesting type h is applied to harvest biomass of type f at the biomass production site i
P^h_{man} = cost to maintain harvesting type h (€ y^{-1})
Y_i^{fg} = integer variable indicating whether or not harvesting type h is applied to harvest biomass of type f at the biomass production site i
P^g_{man} = cost to maintain collection type g (€ y^{-1})
Y_i^{fp} = binary variable indicating whether or not pre-treatment type p is applied to pre-treat product type f at the biomass production site i
P^p_{man} = cost to maintain pre-treatment type p (€ y^{-1})
Y_j^s = binary variable indicating whether or storage facility of type s is opened at location j
P^s_{man} = cost to run storage type s (€ y^{-1})
Y_k^c = binary variable indicating whether or conversion facility of type c is opened at location k
P^c_{man} = cost to run conversion type c (€ y^{-1})

Similar to the economic objective, the **energetic objective** maximises the annualised total energy output considering the annual amount of bioenergy (electricity, heat, biofuel) produced by the conversion facilities minus the energy needed to transport the raw biomass materials, the intermediate products and by-products, the energy needed for harvesting, for collection and local transport and for pre-treatment operations. Furthermore, the objective takes into account the amount of energy needed to run the storage and conversion facilities and to bring the harvesting and collection equipment to the biomass production site.

The **environmental objective** is to minimise the CO_2 equivalent greenhouse gas (GHG) emissions considering the emissions produced by the transport of the raw biomass materials, the intermediate products and by-products, the emissions during harvesting, emissions during collection and local transport and emissions during pre-treatment operations. Also here, the MILP considers GHG emissions to run the storage and conversion facilities and to bring the harvesting and collection equipment to the biomass production site. In accordance with the economic and energetic objective, the environmental objective doesn't consider the CO_2 equivalent greenhouse gas assimilated in the harvested biomass by photosynthesis because the MILP doesn't intend to optimise biomass production practices.

2.3 Constraints

In the proposed MILP, seven major groups of constraints are distinguished to impose physical or regulatory limitations on the considered B4B supply chain.

The first group of constraints regulates the operations performed at the **biomass production site** (i.e. supply node). Since the MILP is developed as a transhipment problem, a supply constraint defines for each biomass production site i that the total quantity of biomass of product type f harvested at the site cannot exceed the available quantity of biomass of product type f grown on that site ($Sup^f_{i\ max}$) (Eq. 9). Furthermore, a pre-treatment constraint defines the product transformation from product type f to product type r during pre-treatment type p applying a transformation coefficient Q^{fpr} (Eq. 10). For example, wood branches (f) can be chipped (p) to wood chips (r) (Q^{fpr}=1), but grass cannot be chipped (Q^{fpr}=0). Extra mass balance constraints conserve the quantity of raw materials or intermediate products entering and leaving the harvesting, collection and pre-treatment operations at the biomass production site. The number of harvesting and collection units required in the supply chain are defined by capacity constraints (cf. Eq. 11). The allowed combinations between the product types and the harvesting, collection and pre-treatment operations are defined as constraints using binary parameters (L) (cf. Eq. 12). The binary parameters define whether or not an operation can occur in combination with another operation or whether or not an operation can be applied to a certain product type. For example, the constraint in equation 12 defines whether or not a biomass type f can be pre-treated by a pre-treatment type p.

$$Sup_{i\ max}^f \geq \sum_h X_i^{fh} \quad \forall\, i \in I, f \in F \quad \text{Eq. 9}$$

With:
$Sup^f_{i\ max}$ = total amount of biomass type f grown at biomass production site i (Mg y^{-1})
X_i^{fh}= amount of biomass type f harvested by harvesting type h at biomass production site i (Mg y^{-1})

$$pN_i^{pr} = \sum_f \left[X_i^{fp} \cdot (1 - \Delta^p) \cdot Q^{fpr} \right] \quad \forall\, i \in I, r \in F, p \in P \quad \text{Eq. 10}$$

With:
pN_i^{pr} = amount of intermediate product type r resulting from pre-treatment type p at biomass production site i (Mg y^{-1})
X_i^{fp}= amount of product type f pre-treated by pre-treatment type p at biomass production site i (Mg y^{-1})
Q^{fpr} = transformation coefficient defining the product transformation from product type f to product type r during pre-treatment type p (0-1)
Δ^p = fraction defining the product loss during pre-treatment type p

$$\frac{X_i^{fh}}{\rho^f} \leq hCAP_{max}^h \cdot Y_i^{fh} \quad \forall\, i \in I, f \in F, h \in H \qquad \text{Eq. 11}$$

With:
X_i^{fh}= amount of product type f harvested by harvesting type h at biomass production site i (Mg y^{-1})
ρ^f = bulk density of product type f (Mg m^{-3})
$hCAP^h_{max}$ = maximum capacity of harvesting type h (m^3 y^{-1})
Y_i^{fh} = binary variable defining whether or not product type f is harvested by harvesting type h at biomass production site i

$$L^{fp} \geq Y_i^{fp} \quad \forall\, i \in I, f \in F, p \in P \qquad \text{Eq. 12}$$

With:
L^{fp} = binary parameter defining whether or not product type f can be pre-treated by pre-treatment type p
Y_i^{fp} = binary variable defining whether or not product type f is pre-treated by pre-treatment type p at biomass production site i

The second group of constraints is related to the **storage facilities**. As mentioned previously, the storage facility corresponds to the transhipment node in the transhipment problem. Therefore, mass balance constraints determine that the quantity of raw material, intermediate products or by-products leaving the storage facility cannot exceed the quantity of raw material, intermediate products or by-products delivered at the storage facility taking into account the possibility that the incoming product is pre-treated during storage. Also here the product transformation during the pre-treatment operation is defined by a transformation coefficient Q^{fpr} (similar to equation 10). Furthermore, a capacity constraint limits the quantity of products delivered at the storage facility (Equation 13). Because not every product type can be stored in each storage type and the available pre-treatment type depends on the storage type, binary parameters define the allowed combination between product type f and storage type s and between storage type s and pre-treatment type p. These binary parameters are used in constraints similar to equation 12.

$$\sum_f \frac{W_{in\,j}^{fs}}{\rho^f} \leq sCAP_{j\,max}^s \cdot Y_j^s \quad \forall\, j \in J, s \in S \qquad \text{Eq. 13}$$

With:
$W^{fs}_{in\,j}$ = amount of product type f delivered at the storage facility of storage type s at location j (Mg y^{-1})
ρ^f = bulk density of product type f (Mg m^{-3})
$sCAP^s_{j\,max}$ = maximum capacity of a storage facility of storage type s at location j (m^3 y^{-1})
Y_j^s = binary variable defining whether or not storage type s is opened at storage site j

The third group of constraints deal with the control of the operations at the **conversion facility**. In this transhipment problem, the conversion facility corresponds to the demand node. Therefore, mass balance constraints define that the quantity of products converted during the conversion process cannot exceed the quantity of products delivered at the conversion facility. Also in this group, a pre-treatment constraint defines the product transformation from product type f to product type r during pre-treatment type p (cf. Eq. 10). Similar to the pre-treatment constraint, the type and quantity of the by-products produced during the conversion process are defined by a transformation coefficient (Q^{fcr}). Capacity constraints define the quantity of raw biomass materials, intermediate products and rest products to be delivered at the conversion facility (cf. Eq. 13) and the maximum bioenergy output of the conversion facility (Eq. 15). The bioenergy output produced at each conversion facility (E_k^{co}) is defined by equation 14. Furthermore, constraints are included to define the allowable mixture of product types in the conversion process, to limit the moisture content of that mixture and to limit the particle size of the product types converted during the conversion process. Binary parameters define the allowed product types for each conversion type (L^{fc}) and the allowed pre-treatment types at the conversion type (L^{cp}) (cf. Eq. 12).

$$E_k^{co} = \sum_f \left(\eta^{co} \cdot U_k^{fc} \cdot LHV^f \cdot L_{th}^c\right) + \sum_f \left(\eta^{co} \cdot U_k^{fc} \cdot LHV^{bg} \cdot \rho_{bg}^f \cdot L_{bg}^c\right) \quad \forall\, k \in K, c \in C, o \in O \qquad \text{Eq. 14}$$

With:
E_k^{co} = amount of bioenergy of type o produced at conversion facility of conversion type c at location k (MWh y^{-1})
η^{co} = conversion efficiency of conversion type c for bioenergy production of type o
U_k^{fc} = amount of product type f converted in conversion facility of type c at location k (Mg y^{-1})
LHV^f = lower heating value of biomass type f (MWh Mg^{-1})
LHV^{bg} = lower heating value of biogas (MWh Mg^{-1})
L^c_{th} = binary parameter indicating whether or not conversion type c produced heat to be converted to electricity or heat
L^c_{bg} = binary parameter indicating whether or not conversion type c produces biogas to be converted to electricity or heat
ρ^f_{bg} = biogas density of biomass type f (Nm^3 Mg^{-1})

$$E_k^{co} \leq cCAP^{co} \cdot Y_k^c \quad \forall\, k \in K, c \in C, o \in O \qquad \text{Eq. 15}$$

With:
E_k^{co} = amount of bioenergy of type o produced at conversion facility of conversion type c at location k (MWh y^{-1})
$cCAP^{co}$ = output capacity of conversion type c in terms of production of bioenergy type o (MWh y^{-1})
Y_k^c = binary variable indicating whether or conversion facility of type c is opened at location k

The fourth type of constraints regulates the **flow** of raw materials and intermediate products from the biomass production site to the storage or conversion facilities and the flow of raw materials, intermediate products and by-products between operation facilities taking into account the available (multimodal) transportation network (cf. Eq. 16). Furthermore, constraints are included defining that the **product flow** from or to a facility can only be greater than zero, if the facility exists (cf. Eq. 17).

$$W_{in\,j}^{fs} = \sum_{i,z} X_{ij}^{fsz} + \sum_{l,u,z} X_{lj}^{fusz} + \sum_{k,c,z} X_{kj}^{fcsz} \quad \forall\, f \in F, j \in J, s \in S \qquad \text{Eq. 16}$$

With:
$W_{in\,j}^{fs}$ = amount of product type f delivered at the storage facility of storage type s at location j (Mg y^{-1})
X_{ij}^{fsz} = amount of product type f transported by transport type z from biomass production site i to the storage facility of storage type s at location j (Mg y^{-1})
X_{lj}^{fusz} = amount of product type f transported by transport type z from the storage facility of storage type u at location l to the storage facility of storage type s at location j (Mg y^{-1})
X_{kj}^{fcsz} = amount of product type f transported by transport type z from the conversion facility of conversion type c at location k to the storage facility of storage type s at location j (Mg y^{-1})

$X_{ik}^{fcz} \leq cCAP_{max}^{c\,in} \cdot Y_k^c$ Eq. 17

$\forall f \in F, j \in J, s \in S, k \in K, c \in C, z \in Z$

With:

X_{ik}^{fcz} = amount of product type f transported by transport type z from biomass production site i to the conversion facility of conversion type c at location k (Mg y^{-1})
$cCAP^{c\,in}_{max}$ = maximum feeding rate of a conversion facility of conversion type c (Mg y^{-1})
Y_k^c = binary variable defining whether or not conversion facility of conversion type c is opened at location k (0-1)

Fifthly, the **demand** constraint ensures that the demand for each bioenergy type (e.g. heat, electricity) is met for the whole region (Eq. 18). The surplus of bioenergy generated in the supply chain is limited to a certain fraction of that demand ($E^o_{surplus}$) (Eq. 19).

$$E^o_{surplus} = \left(\sum_k \sum_c E_k^{co}\right) - D^o \quad \forall o \in O \qquad \text{Eq. 18}$$

With:

$E^o_{surplus}$ = total surplus of bioenergy of type o (MWh y^{-1})
E_k^{co} = amount of bioenergy of type o produced at conversion facility of conversion type c at location k (MWh y^{-1})
D^o = demand of bioenergy type o in the whole region (MWh y^{-1})

$$E^o_{surplus} \leq Q^o \cdot D^o \quad \forall o \in O \qquad \text{Eq. 19}$$

With:

$E^o_{surplus}$ = surplus of bioenergy of type o generated in the supply chain (MWh y^{-1})
Q^o = parameter defining the allowed fraction of energy surplus
D^o = demand of bioenergy type o in the whole region (MWh y^{-1})

The sixth group contains the **non-negativity** constraints reinsuring that all variables are non-negative. Exception to this rule are the variables defining the total energy output (E_{tot}) and the total profit of the supply chain (PROFIT) which can also be negative.

The final group of constraints reinsures that the variables determining the application of a harvesting or collection operation are **integers**. This allows the model to define the number of harvesting and collection units needed in the supply chain. **Binary** constraints reinsure that the variables applying a pre-treatment operation or opening a storage or conversion facility can be 0 or 1.

2.4 Parameters

The MILP model requires a variety of parameters. Non-spatial parameters characterise each product type and operation type in the supply chain. An overview of the required non-spatial parameters is given in tables I to VIII in section 4. Furthermore, the regional demand for each bioenergy type (MWh y^{-1}), the market price for green certificates (€ MWh^{-1}) and the rate for each bioenergy type (€ MWh^{-1}) must be defined by the user. Binary parameters (L) indicate the possible combinations between biomass types and harvesting types, between biomass types and collection types, between biomass types and pre-treatment types, between biomass types and storage types, between biomass types and conversion types, between storage types and pre-treatment types and between conversion types and pre-treatment types. The spatial parameters required in the MILP are derived from the (multimodal) transportation network and the location of biomass production sites, storage sites and conversion sites being the shortest network distances between all biomass production, storage and conversion sites. Also, the area of each biomass type at each production site is needed.

3 SYSTEM IMPLEMENTATION

The MILP model is implemented in the optimisation software LINGO. The scenario analysis is performed with an Intel Core i5 CPU 2.67 GHz with 4 GB RAM on a 64-bit platform. The computational intensity of the MILP depends on the number of variables, more specifically the number of integer variables.

The needed parameters are stored in a PostgreSQL database with PostGIS extension [11]. This database encompasses a spatial and a non-spatial component. The non-spatial component covers the possible types of biomass and the possible techniques to harvest, collect, store, pre-treat and convert with their attributes on the one hand, and their mutual relationships on the other hand (i.e. binary parameters) [11]. The multimodal transportation network and the location and characteristics of the biomass production sites, storage sites and conversion sites are maintained in the spatial component of the database. This spatial information can be visualised and pre-processed by users of geographic information system (GIS) softwares. Furthermore, the GIS functions are applied to determine the shortest distance between all sites over the different transportation networks.

4 USE CASE: LIMBURG (BELGIUM)

4.1 LIHD biomass supply chain

The functionalities of the proposed MILP are analysed for a B4B supply chain where the biomass is supplied from low input high diversity (LIHD) biomass systems in Limburg, a province in Belgium (i.e. 2 422 km²). The LIHD biomass systems include habitats such as (semi-) natural grasslands, heath lands, swamps, multifunctional forests and small landscape elements (e.g. road verges). Regular mowing with removal of management is indispensable to maintain or enlarge the value for production and nature [26] or to guarantee traffic safety (e.g. roadsides, masking trees, etc.). Whereas currently these management residues are usually left behind as waste product [27], it is assumed that LIHD biomass will become a valuable source of biomass to meet the increasing demand for bioenergy [26], [27]. In this paper the main goal is to illustrate the potential of the MILP. The values of the parameters are adopted from or derived from a variety of literature resources.

This use case concentrates on LIHD biomass, more specifically on grass and brushwood. All locations of grassland and brushwood production sites of at least 50 ha are selected from the biological value map [28]. As presented in figure 3, 46 **biomass production sites** are selected representing 36 167 ha of grass and 2 536 ha of brushwood. The characteristics of the available biomass types are summarised in table I.

Table I Parameters of the available biomass types

		Grass	Brushwood
MC	(%)	75	45
LHV	(MWh Mg^{-1})	0.811	0.687
HBP	(Mg ha^{-1} y^{-1})	2.1	3.5

MC = moisture content
LHV = lower heating value
HBP = harvestable biomass production

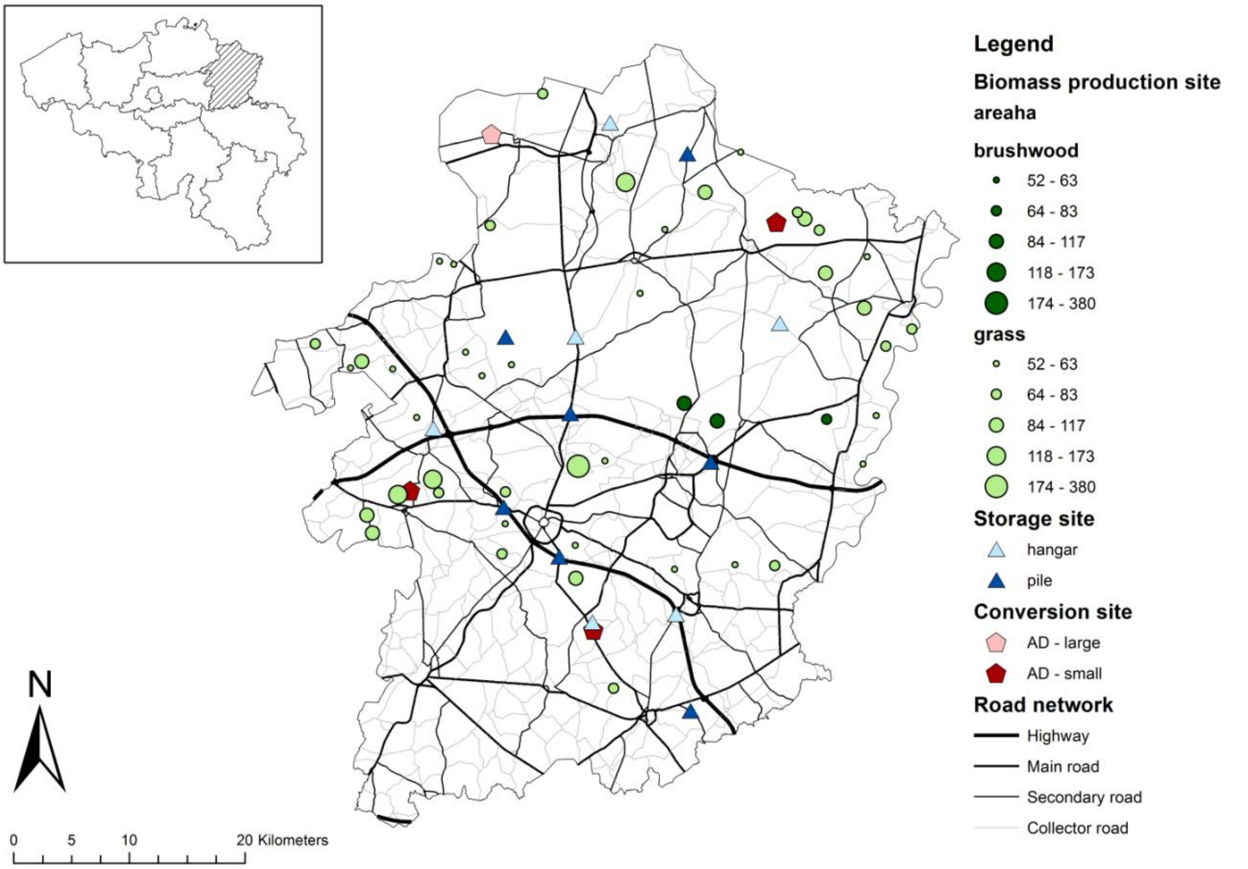

Figure 3 Biomass supply network of Limburg (without Voeren) as analysed in the use case (references: [28], [29], [31])

To harvest grass and brushwood a variety of harvesting equipment can be used. However, in this paper only the two most common ones are selected. The disc mower cuts off the vegetation with rotating discs causing little damage to the vegetation. The flail mower strikes the vegetation at speed, beating off and diminishing the vegetation. The clippings are highly fragmented and reduced which complicates the collection (i.e. higher product loss). A binary parameter indicates that grass can be mown with a disc mower or a flail mower and that brushwood can only be harvested with a flail mower. Table II summarises the main parameters of the harvesting types included in the MILP with indicative values.

Table II Parameters characterising the harvesting types

		Disc mower	Flail mower
CAP^h_{max}	(m^3 y^{-1})	11 000	15 000
v^h	(km h^{-1})	8	11
w^h	(m)	2.82	1.80
E^h	(GJ h^{-1})	0.103	0.142
P^h	(€ h^{-1})	30	35
GHG^h	(kg CO_2 eq h^{-1})	8.88	12.21

CAP^h_{max} = maximum capacity of harvesting type h
v^h = harvesting speed of harvesting type h
w^h = harvesting width of harvesting type h
E^h = energy input during harvest with harvesting type h
P^h = cost to harvest with harvesting type h
GHG^h = GHG emissions during harvest with harvesting type h

To collect the harvested grass and brushwood two collection types are considered, i.e. a tractor with trailer and a mow-load combination. A tractor with trailer is the most general collection option. It is used to collect biomass some time after the cut (with or without combined pre-treatment operation). The mow-load combination immediately collects the biomass during the cutting operation. Therefore, it is assumed that no extra energy is consumed, no extra operation cost is required and no extra GHG emissions are produced. The binary parameter indicates that grass mown with a disc mower can be collected by both collection types while grass and brushwood mown with a flail mower can only be collected by a mow-load combination. Furthermore, the binary parameter indicates that grass chopped and/or dried on the biomass production site can only be collected with a trailer while brushwood will be chopped immediately during collection with the mow-load combination and drying is not possible.

Table III Parameters characterising the collection types

		Trailer	Mow-load
CAP^g_{max}	(m^3 y^{-1})	18 000	15 000
Product loss	(%)	5	1
E^g	(GJ Mg^{-1} km^{-1})	4.29	0
P^g	(€ Mg^{-1} km^{-1})	0.47	0
GHG^g	(kg CO_2 eq Mg^{-1} km^{-1})	0.303	0

CAP^g_{max} = maximum capacity of collection type g
E^g = energy input during collection with collection type g
P^g = cost to collect with collection type g
GHG^g = GHG emissions during collection with collection type g

Due to a lack of data, the storage sites are fictitious. Thirteen **storage facilities** are considered. Four storages are located near a highway access point, four storages are located at an intersection where transhipment between tractor and truck is required to allow further transport and five storages are located near areas where several biomass production sites are gathered. The parameters of the available storage types are summarised in table IV. Figure 3 indicates for each storage site which storage type is available. In the MILP available storage types at each location are defined by $sCAP^{s}_{j\ max}$ defining the maximum capacity in m³ of a storage facility of storage type s at location j. A binary parameter defines that both biomass products and the intermediate products can be stored in a pile except the dried product types and by-products while the dried products can be stored in a hangar.

Table IV Parameters characterising the storage types

		Pile	Hangar
Product loss	(%)	15	2
$\mathbf{E^{s}_{man}}$	(GJ m^{-3})	0.00	0.28
$\mathbf{P^{s}_{man}}$	(€ m^{-3})	0.50	1.95
$\mathbf{GHG^{s}_{man}}$	(kg CO_2 eq m^{-3})	0.20	1.82

E^{s}_{man} = energy input to run a storage facility of type s
P^{s}_{man} = cost to run a storage facility of type s
GHG^{s}_{man} = GHG emitted to run a storage facility of type s

In Limburg province, four **anaerobe digesters** (AD) are registered at the Flemish compost organisation, VLACO (Figure 3). These anaerobe digesters convert manure, agricultural residues and/or organic biological waste into (mainly) biogas and digestate [29]. In each digester the biogas is used to generate heat and electricity using a combined heat and power (CHP) installation. Two types of anaerobe digesters are distinguished: i.e. AD at farm scale (FAD) and AD at industrial scale (IAD). In the city of Lommel, in northern Limburg one industrial anaerobe digester exists [29]. The anaerobe digesters in the cities of Herk-De-Stad, Houthalen-Helchteren and Vliermaal are farm scale anaerobe digesters [29]. The main parameters of the anaerobe digesters are indicated in table V. A binary parameter defines that all biomass products and intermediate products can be converted by anaerobe digestion. Of course, the constraints in the MILP model consider the moisture content, particle size and mixture requirements of the conversion facility to determine the allowed and required product types.

Table V Parameters characterising the conversion types

		Farm scale	Industrial scale
Thermal capacity	(MWh_{th})	28 800	51 686
Electric capacity	(MWh_{e})	24 000	43 072
Thermal efficiency	(%)	47	52
Electric efficiency	(%)	34	38
Min particle size	(mm)	1	1
Max particle size	(mm)	3	3
Min moisture content	(%)	50	60
Max moisture content	(%)	65	80
Min product input	(Mg y^{-1})	19 000	115 000
Max product input	(Mg y^{-1})	24 000	150 000

In order to optimise the supply chain, biomass pre-treatment operations must be introduced to process the harvested biomass to yield the characteristics that will allow efficient storage, transport and conversion [30]. It is assumed that pre-treatment operations can occur at any stage of the supply chain: i.e. at the biomass production site, at the storage site and at the conversion site. A binary parameter indicates that natural drying is possible when products are stored in a pile and that chopping is possible in hangars. Another binary parameter defines that choppers are available at the conversion sites, but drying is not possible any more. A third binary parameter defines which pre-treatment types are applicable to which product types. The parameters of the available pre-treatment types are summarised in table VI. Table VII summarises the parameters of the intermediate products arisen after harvesting, pre-treatment or conversion.

Table VI Parameters characterising the pre-treatment types

		Natural dry	Chop
Product loss	(%)	5	0
$\mathbf{E^{c}_{man}}$	(GJ Mg^{-1})	0	0.18
$\mathbf{P^{c}_{man}}$	(€ Mg^{-1})	0.5	4.00
$\mathbf{GHG^{c}_{man}}$	(kg CO_2 eq Mg^{-1})	0.05	0.55

E^{c}_{man} = energy input to run a conversion facility of type c
P^{c}_{man} = cost to run a conversion facility of type c
GHG^{c}_{man} = GHG emitted to run a conversion facility of type c

Table VII Parameters of the harvested, intermediate and rest products

	MC (%)	LHV (MWh Mg^{-1})	BD (Mg m^{-3})	BP (Nm³ Mg^{-1})	PS (mm)
Disc GR	75	0.811	0.08	180	150
Flail GR	75	0.811	0.11	180	50
Flail BW	45	0.687	0.13	340	50
Dry GR (disc)	55	2.003	0.06	155	150
Dry GR (flail)	55	2.003	0.09	155	50
Dry BW	25	3.416	0.11	300	50
Chop GR	75	0.811	0.18	180	1.5
Chop BW	75	0.687	0.22	340	1.5
Dry chop GR	55	2.003	0.15	155	1.5
Dry chop BW	25	3.416	0.18	300	1.5
Digestate	90	-	1.00	-	3
Dry digestate	40	1.111	1.10	-	3

MC = moisture content
LHV = lower heating value
BD = bulk density
BP = biogas production
PS = particle size
GR = grass
BW = brushwood

Since the supply chain is optimised for a small area (i.e. 2 422 km²), tractor and truck are chosen to be the two possible transport types. The truck transportation network is retrieved from the Multinet dataset [31] including driving directions and restrictions. The tractor transportation network is derived from the Multinet dataset in the sense that tractors are not allowed to access the highway, but are allowed to access roads which are restricted for trucks. The network is presented in figure 3. Table VIII summarises the parameters characterising the considered transport types.

Table VIII Parameters characterising the transport types

		Tractor	Truck
E E_{trans}	(GJ Mg^{-1} km^{-1})	0.0029	0.0014
P_{trans}	(€ Mg^{-1} km^{-1})	0.15	0.09
GHG_{trans}	(kg CO_2 eq Mg^{-1} km^{-1})	0.250	0.062
E_{load}	(GJ Mg^{-1})	0.000	0.005
P_{load}	(€ Mg^{-1})	0.00	2.49
GHG_{load}	(kg CO_2 eq Mg^{-1})	0.0000	0.0072
E_{unload}	(GJ Mg^{-1})	0.005	0.003
P_{unload}	(€ Mg^{-1})	2.00	1.19
GHG_{unload}	(kg CO_2 eq Mg^{-1})	0.0082	0.0032

E_{trans}, E_{load}, E_{unload} = energy input to respectively transport, load and unload
P_{trans}, P_{load}, P_{unload} = cost to respectively transport, load and unload
GHG_{trans}, GHG_{load}, GHG_{unload} = GHG emissions to respectively transport, load and unload

4.2 Scenario analysis

4.2.1 Scenario 1: Base scenario

The first scenario is the base scenario considering the parameters as described above. The thermal and electric demand are determined based on the objective set by the European Commission that Belgium must produce 13 % of the final energy consumption from renewable sources by 2020 and these days 8 % of the renewable energy originates from biogas. This means that from the total heat demand in Limburg (i.e. 724 630 MWh) at least 7 536 MWh must come from biogas and from the total electricity demand of 1 455 469 MWh at least 15 137 MWh is retrieved from biogas. Table IX summarises the main results for the three objectives, i.e. maximal energy output (scenario 1A), maximal profit (scenario 1B) and minimal GHG emissions (scenario 1C). Figure 4 presents the allocation paths for the three objectives.

Scenario 1 shows that no matter which objective is optimised, all biomass is transported to the industrial anaerobe digester (IAD) in the town of Lommel of which the output capacity easily meets the heat and electricity demand. The selection of the IAD is mainly cause by the constraints defining the required moisture content of the biomass mixture in the AD. Since the IAD allows a maximum moisture content of 80 % no additional drying of biomass is required in the supply chain. In comparison, the maximum moisture content allowed in the FAD amounts 65 %. This means that additional drying operations are necessary in the supply chain, leading to higher costs, energy input and GHG emissions due to changes in harvest, collection and pre-treatment operations and perhaps additional storage operations. In this scenario storage facilities are not included in the supply chain. This is mainly due to the scale of the use case which causes the extra cost to manage the storage site to be higher than the cost to transport the products directly to the conversion facility.

Depending on the objective to be optimised, the allocation pattern differs mainly due to small changes in transport distances and transport parameters. From figure 4 it is clear that the larger biomass production sites are allocated in all scenarios (1A to 1C) while the allocation from the smaller biomass production sites differs between the scenarios (1A to 1C). To reduce the GHG emissions only the largest biomass production sites are harvested to reduce the number of operations and to reduce emissions during transport. Furthermore, figure 4 indicates that the neighbouring biomass production sites are harvested while biomass production sites further away are left out. Also here, transportation distances and parameters are decisive.

Table IX indicates that the total energy output ranges between 106 307 and 117 049 GJ y^{-1}. This range is allowed due to the defined surplus of 10 % of the demand. Furthermore, optimisation of the total energy output results in intermediate profit and GHG emissions while optimisation of the total profit results in the highest emissions and optimisation of the GHG emissions results in lowest energy output and lowest profit.

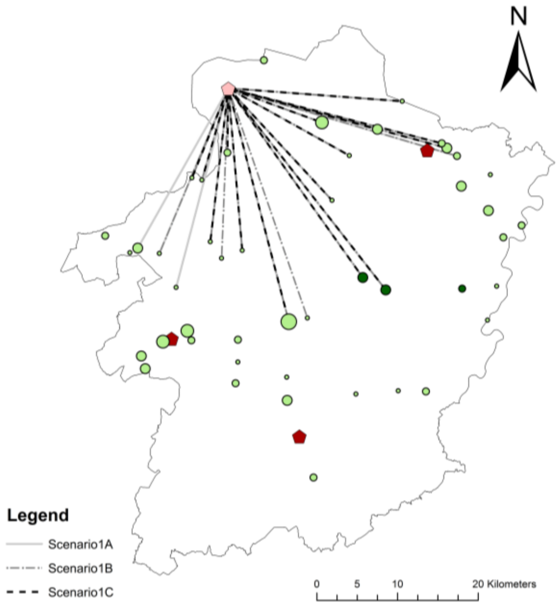

Figure 4 Visualisation of the location – allocation result of scenario 1 and scenario 3

4.2.2 Scenario 2: Centralised vs. decentralised

To investigate how the biomass supply chain changes when only farm scale anaerobe digesters are available, in scenario 2 all four conversion sites contain a farm scale anaerobe digester with electric capacity of 8 000 MWh. This forces the MILP model to include more than one anaerobe digester to meet the heat and electricity demand. This conversion facility requires a maximum of 20 000 ton biomass per year. Table IX summarises the main results for the three objectives, i.e. maximal energy output (scenario 2A), maximal profit (scenario 2B) and minimal GHG emissions (scenario 2C). Figure 5 presents the allocation paths for the three objectives.

Scenario 2 shows that three out of four farm scale anaerobe digesters are opened to meet the demand. To meet the required biomass input at each facility more biomass production sites are harvested than in scenario 1. Although three anaerobe digesters are include the operation types in the supply chain are still the same.

Figure 5 shows that the harvested biomass production sites are located in the neighbourhood of the opened conversion facilities to reduce transportation costs. However, in some production sites the biomass is allocated to several conversion facilities. This is inter alia the case for brushwood which is needed in the conversion facilities to reduce the moisture content of the biomass mixture in the anaerobe digester.

As in scenario 1, optimisation of the total energy output results in intermediate profit and GHG emissions while optimisation of the profit results in the highest emissions and optimisation of GHG emissions results in lowest energy output and lowest profit. In comparison with scenario 1, scenario 2 results in a higher total energy output and a higher total profit probably due to the higher amount of biomass converted in the supply chain and the decentralised conversion of biomass resulting in shorter transportation distances and therefore smaller transportation costs. This also results in smaller total GHG emissions in comparison with scenario 1.

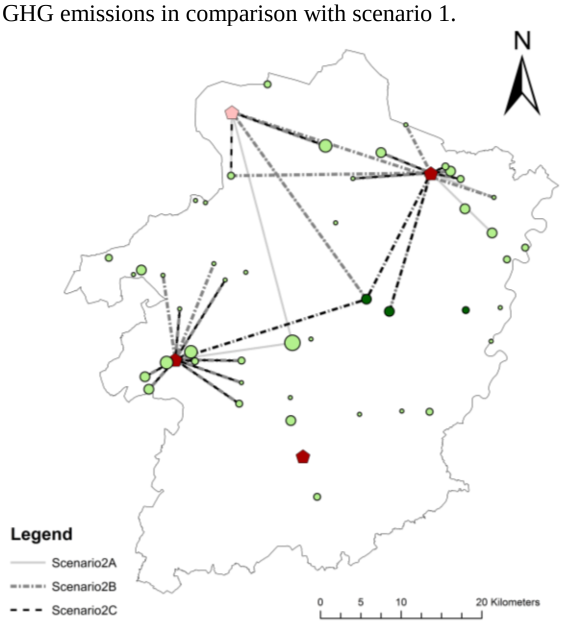

Figure 5 Visualisation of the location – allocation result of scenario 2

4.2.3 Scenario 3: No governmental incentives

As mentioned before, the total revenue of the supply chain is determined by the energy price and the governmental incentives (i.e. green current certificates (i.e. currently 106.87 € MWh^{-1}) and heat and power certificates (i.e. currently 37.32 € MWh^{-1}) [32]) (Eq. 2). This scenario investigates how and if the biomass supply chain changes when all governmental incentives are withdrawn and transport costs rise (e.g. with factor 5). Table IX summarises the main results for the three objectives, i.e. maximal energy output (scenario 3A), maximal profit (scenario 3B) and minimal GHG emissions (scenario 3C).

The results indicate that withdrawing the governmental support and increasing transportation costs has no immediate influence on the configuration of the supply chain. Except that the tractor is not any longer included to transport the biomass when the total profit of the supply chain is optimised. This is easily explained because the transportation costs by truck are significantly lower per ton per km in comparison with a tractor. However, in comparison with scenario 1 the total profit decreases significantly due to high transport costs and lack of support. Although the values used in this use case have a more indicative and illustrating purpose, it is clear that governmental support contributes significantly to the economic benefits of the supply chain encouraging the production of biogas.

Table IX Summary of the results of the three scenarios

	E_{tot} (GJ y^{-1})	PROFIT (€ y^{-1})	GHG_{tot} (kg CO_2 eq y^{-1})	Biomass location	Storage location	Conversion location	Harvest type	Collection type	Pre-treat type	Transport type	Time (s)
1A	**117 049**	6 022 147	1 878 906	BW: 2 GR: 17	0	1 IAD	Flail	Mow-load	Chop at CL	Truck	48
1B	111 624	**6 047 466**	1 957 138	BW: 2 GR: 17	0	1 IAD	BW: flail GR: disc	BR: Mow-load GR: trailer	BR: chop at BPS GR: chop at CL	Tractor Truck	21
1C	106 307	5 485 617	**1 866 087**	BW: 2 GR: 13	0	1 IAD	Flail	Mow-load	Chop at CL	Truck	19
2A	**118 407**	6 200 654	1438876	BW: 2 GR: 19	0	3 FAD	Flail	Mow-load	Chop at CL	Truck	366
2B	112 284	**6 259 865**	1 531 820	BW: 2 GR: 20	0	3 FAD	BW: flail GR: disc	BR: Mow-load GR: trailer	BR: chop at BPS GR: chop at CL	Tractor Truck	24
2C	108 885	5 720 363	**1 429 287**	BW: 2 GR: 17	0	3 FAD	Flail	Mow-load	Chop at CL	Truck	12
3A	**117 049**	-23 178	1 878 906	BW: 2 GR: 17	0	1 IAD	Flail	Mow-load	Chop at CL	Truck	46
3B	111 266	**8 835**	1 897 972	BW: 2 GR: 17	0	1 IAD	BW: flail GR: disc	BR: Mow-load GR: trailer	BR: chop at BPS GR: chop at CL	Truck	132
3C	106 307	-30 415	**1 866 087**	BW: 2 GR: 13	0	1 IAD	Flail	Mow-load	Chop at CL	Truck	18

BW = brushwood
GR = grass
IAD = industrial anaerobe digester
FAD = farm scale anaerobe digester

6 DISCUSSION AND CONCLUSION

One of the most important barriers hampering the development of a strong bioenergy sector is the complexity and cost of the (upstream) biomass-for-bioenergy supply chain [5]. This cost mainly relates to the handling and transport of biomass from the source location to the conversion facility inducing a variety of economic, energetic and environmental implications [4]. To address this problem, this paper introduces a mixed-integer linear programming model which is meant to optimise the designed B4B supply chain maximising the total energy output, maximising the total profit or minimising total GHG emissions. According to the chosen objective, the optimisation model determines the optimal location, technology and capacity of storage, pre-treatment, and conversion facilities. In addition, it returns the optimal allocation of biomass and intermediate products from biomass production sites to operation facilities and of biomass, intermediate products and by-products between the operation facilities. The MILP is constrained by supply chain restrictions, the available multimodal transportation network and the interrelationship between operations.

To illustrate the functionalities of the MILP model, it is applied to a simplified B4B supply chain based on low input grass and brushwood systems in Limburg, a province of Belgium. The scenario analysis confirms the response capacity of the MILP to changes in information considered in the initial planning. It also shows that different scenarios (e.g., different capacity of conversion facilities, different support) and different objectives can result in alternative optimal location-allocation solutions and different corresponding computation times.

Furthermore, the scenario analysis indicates that the MILP model is an inspiring tool to investigate the consequences of governmental decisions, of introducing new biomass material, a new conversion facility, etc. Also, the MILP allows determining the optimal location, type and capacity for a new storage or conversion facility among a set of potential locations. This implies that the MILP can be used by stakeholders with different kinds of perspectives of the same problem. For example the government may intend to consider the complete supply chain to make decisions regarding e.g. support decisions while the owner of a conversion facility may be rather interested in the optimal location of the biomass production sites or storage sites. In the proposed MILP, binary variables define whether or not an operation is applied or a facility is opened. This allows users to force certain operations or facilities to be closed or open by fixing the value of the binary variable in advance. In this way the user can define the existing facilities or operations available in the supply chain prior to the optimisation.

The main critical point in the implementation of this model is the difficulty to identify reliable quantitative values for the various model parameters. Therefore, progress in other fields of research in order to provide reliable quantitative information (such as the agricultural materials properties, the conversion process efficiency and yields, various costs, land availability etc.) is a critical factor in the performance and the applicability of the present work in real situations [33]. In this paper the main goal is to illustrate the potential of the MILP. Although the values of the parameters are adopted from or derived from literature resources, a background check of the data is required. This implies that the results indicate a direction of change, but do not intend to present the most realistic values. Secondly, a major challenge in the development of this MILP model is to limit computational times when the number of operations and facilities increases to represent the real world. Indeed, due to the complexity of the model and the large number of integer variables, computations last a significant time when changing parameter values and adding more possible operation types and locations. The possibilities of clustering algorithms or other heuristic algorithms need to be evaluated to allow application to a larger area.

Future work entails the expansion of the presented MILP model to support the optimisation of the supply chain considering the temporal variability in supply of biomass and demand of bioenergy. Also the cyclicity in the production of biomass must be considered for determining the optimal moment to harvest the biomass. This cyclicity implies that mowing today affects the availability and composition of tomorrow's biomass.

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