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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

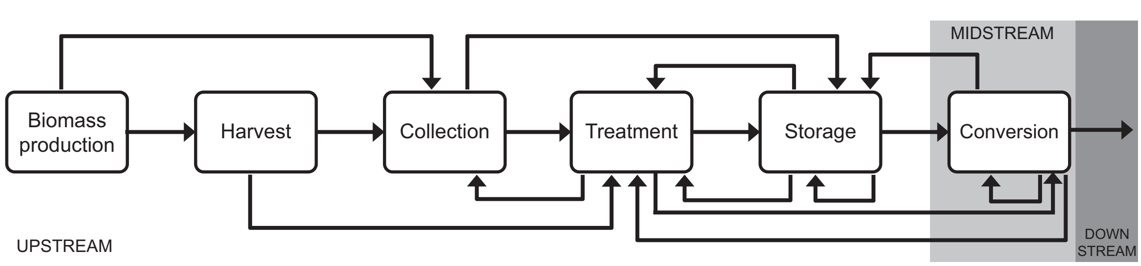

Fig. 1. High level process model of the biomass supply chain representing the sequence of operations. The boxes represent the 6 key operation types distinguished in the upstream segment while the arrows indicate the possible material flows between the key operations [23].