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A reference data model to support biomass supply chain modelling and optimisation

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ABSTRACT

This paper presents a generic and flexible reference data model meant as the blueprint of the database component of information and decision support systems related to different types of biomass-based supply chains (e.g. first to fourth generation biomass for production of bioenergy and biomaterials). The data model covers the biomass types and handling operations as characterised by their attributes and mutual relationships resulting from a life cycle inventory analysis. The data model enables the identification of the possible operation sequences in the specified chain. This functionality is demonstrated in a case study in which biomass from tall herb communities and mesotrophic grasslands is supplied for biogas or compost production. A comparative analysis has pointed out that the data model includes the required object types to add specific attributes of biomass supply chain simulation and optimisation models (such as spatial and temporal dimensions).

Software availability

PostgreSQL: –PostgreSQL Global Development Group – http://www.postgresql.org/about/contact/. –Availability: http://www.postgresql.org/download/. –Cost: Free. –Year first available: 1996. –Version used: 9.1. –Version available at the moment of publication: 9.5.2. –Hardware required: In general, a modern Unix-compatible platform should be able to run PostgreSQL. –Software required: GNU make version 3.80 or newer and ISO/ANSI C compiler (at least C89-compliant). –Program language: C. –Program size: 63 MB

1. Introduction

The “Climate Action and Renewable Energy Package” of the European Union encourages the EU member states to improve their energy efficiency and to promote alternative and renewable energy sources in order to reduce greenhouse gas emissions and fossil fuel dependency (European Commission, 2010a). Studies forecasting the use of alternative and renewable energy sources in 2050 indicate that biomass will occupy a significant share (40–50%) in the production of electricity, heat and transport fuels (Dufresne et al., 2009; IPCC, 2011; Singer et al., 2011) because biomass is abundantly present and it can be stored to generate energy on demand (Mafakheri and Nasiri, 2014; Rentizelas et al., 2009b). In addition, biomass can also be a sustainable alternative for the currently fossil based production of chemicals and medicines such as cosmetics and food additives and materials such as bioplastics and paper. Unfortunately, uncertainties related to weather variability, policy conditions and market fluctuations (Shabani et al., 1998) as well as the barriers induced by high costs for transport and handling of biomass feedstock (Gold and Seuring, 2011; Shabani et al., 1998) have prevented the bio-based sector from making a greater contribution to the present market.

To address these prohibiting factors for the take-off of bio-based systems, recent research efforts combine supply chain management and operations research (De Meyer et al., 2014; Mafakheri and Nasiri, 2014; Shabani et al., 1998; Sharma et al., 2013). Most of the developed optimisation models address a specific (part of the) supply chain for a specified biomass type (De Meyer et al., 2014). Since most barriers for the development of a sustainable bio-based

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sector relate to the characteristics of the biomass products, most optimisation models and simulation models address the upstream part of the supply chain (De Meyer et al., 2014; Shabani et al., 1998; Sharma et al., 2013). This implies that the operations are considered from biomass production up to the delivery to the conversion facility. Each of these models comes with its own database or its own way to structure the input data needed in the optimisation model (Ayoub et al., 2007; De Mol et al., 1997; Freppaz et al., 2004; Frombo et al., 2009). De Mol et al. (1997) store all data concerning possible network structures in their database, such as costs, capacities, storage losses and seasonality in supply and demand. These data are transferred to the optimisation model by writing them to ASCII files (De Mol et al., 1997). The database developed by Ayoub et al. (2007) covers the data of biomass resources for a pre-defined country or region. Data mining techniques are used to determine the optimal locations of facilities, available biomass quantities and the allocation of biomass feedstock based on spatial distribution (Ayoub et al., 2007). Freppaz et al. (2004) and Frombo et al. (2009) both come with a relational database connected to the optimisation model by means of an open database connectivity (ODBC) interface. Both databases cover the input data of the optimisation model required to characterise the problem (Freppaz et al., 2004; Frombo et al., 2009). None of the publications describes the data model in sufficient detail to allow re-use.

These different approaches and the lack of transparency on the data structure hamper the application of the simulation and optimisation models to other types of supply chains than the one for which they have been developed and constraints the exchange of the models among users. A ‘reference’ data model can purvey genericity and model interoperability by enabling the representation of typical biomass supply chains capturing different sorts of products, operations and attributes. This would result in a holistic platform that is capable of addressing different types of problems for different types of biomass-based supply chains and different optimisation or simulation models. Such unifying frameworks support analysis of alternatives with stakeholders and assessing and communicating their results in a transparent way (Kelly et al., 2013). In addition, a generic reference data model is a precondition to achieve a standard exchange format. Data (in case studies) can then be made public in a usable (XML) format, so that different tools can be benchmarked in the same case studies. The need for standardisation in modelling and data transfer has also been recognised in other fields such as ecosystem modelling (Mooij et al., 2014), hydrogeology (Wojda and Brouyère, 2013), soil survey (de la Rosa et al., 2002), space physics (Todd et al., 2010), public transport (Comité Européen de Normalisation, 2001), medical care (Beeler, 1998; Canfield et al., 1994) and financial support (Ecofin Data Model AG, 2006). Furthermore, the data model should be spatially enabled for visualisation of the problem and/or computation of spatial parameters (absolute and relative locations) involved in the problem (Ayoub et al., 2007; de la Rosa et al., 2002; Frombo et al., 2009; Perpina et al., 2009).

This paper ambitions to present a generic and flexible reference data model, based on knowledge-based engineering (Kelly et al., 2013), meant as the blueprint of the database component of information and decision support systems related to typical biomass-based supply chains (e.g., agricultural and silvicultural crops and residues, sewage sludge, municipal solid waste, industrial residues and animal residues for production of bioenergy and biomaterials). Such knowledge based models are often used in Expert Systems in which the quality of the model is decisive for the succes of the system (Kelly et al., 2013). Section 2 describes the procedure used to design and validate the reference data model, while Section 3 presents the resulting conceptual data model, its physical implementation and an exercise for validation of its genericity and applicability. This results in the evaluation of the reference data model and the definition of opportunities for its further elaboration (Section 4).

2. Methodology

2.1. Design of the reference data model

In general, decision support systems (DSS) described in the field of biomass supply combine three modules: (1) a database module, (2) a query module and (3) a decision module (Fig. 1) (Freppaz et al., 2004; Frombo et al., 2009; Lin et al., 2015; Zambelli et al., 2012). The database module stores the input data of the optimisation or simulation model to characterise the problem and the supply chain to be analysed. These input data encompass non-georeferenced data such as the characteristics of operations and georeferenced data such as the characteristics of biomass production sites and operation facilities. To enable users to organise, visualise and process the spatial input data and results, the database module is linked to a GIS-based query module. The decision module encompasses the tool to optimise or simulate the specified biomass-based supply chain.

The reference data model, presented in this paper, is meant as the blueprint of the database module in this general architecture. This implies that the data model must be generic to make it applicable to different types of biomass-based supply chains, from first to fourth generation biomass (e.g. agricultural and silvicultural crops and residues, sewage sludge, municipal solid waste, industrial residues and animal residues) used for bio-energy and/or biomaterial production. In addition, the data model must cover the input data needed in different optimisation or simulation models or must be flexible to enable easy addition, deletion or change of object types, attributes and attribute values.

The design of the reference data model is based on conceptual framework to address design science, proposed by Wieringa (Wieringa and Heerkens, 2006; Wieringa, 2009): (1) problem investigation, (2) solution design, (3) design validation, (4) choice of a solution, (5) implementation of the chosen solution and (6) evaluation of the implementation (Wieringa and Heerkens, 2006; Wieringa, 2009).

The problem investigation (step 1) entails the definition of a generic high level process model based on a generic cradle-to-gate life cycle inventory (LCI) (Chen, 1988; Storey, 1991) to obtain an in-depth insight in the possible product and operation types and their relationships in biomass-based supply chains. An LCI is the stage in a life cycle assessment (LCA) in which the processes and elementary flows of the life cycle are identified (and quantified in case of a specific case) (European Commission, 2010b). An LCI usually

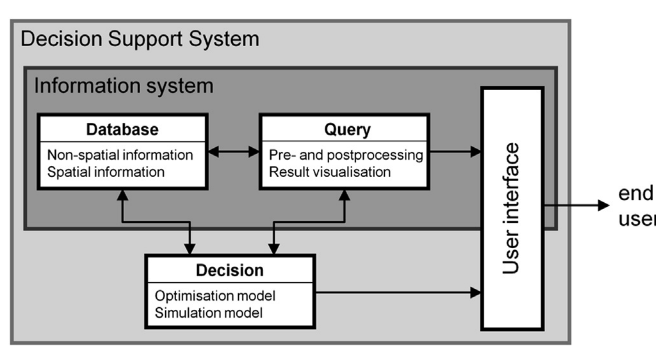

Fig. 1. General architecture of a spatio-temporal decision support system for biomass-based supply chains (De Meyer et al., 2013b).