Generic data model to represent the biomass-to-bioenergy supply chain logistics

Annelies De Meyer[1*], Dirk Cattrysse[2], Monique Snoeck[3], Jos Van Orshoven[1]

[1] *Department of Earth & Environmental Sciences, Division Forest, KU Leuven, Celestijnenlaan 200E, 3001 Leuven, Belgium*
[2] *Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300A, 3001 Leuven, Belgium*
[3] *Department of Decision Sciences and Information Management, KU Leuven, Naamsestraat 69, 3000 Leuven, Belgium*
* *Corresponding author. E-mail: annelies.demeyer@ees.kuleuven.be*

Abstract

Based on a literature review, we conceived the architecture of a spatial (& temporal) decision support system (s(t)DSS) that addresses the optimisation of the biomass-to-bioenergy supply chain logistics. In this DSS, three integrated modules will be at stake: (i) a generic and flexible database, (ii) a query tool and (iii) an optimisation tool. This paper focuses on the description of the database module, consisting of a spatial and a non-spatial component. Based on an in-depth analysis of the biomass-to-bioenergy supply process, the non-spatial data model is developed covering the types of biomass and the techniques for harvest, collection, storage, pre-treatment and conversion with their attributes on the one hand, and their mutual relationships and possible sequences on the other hand. This non-spatial data model allows the determination of all possible operation sequences from a certain biomass type to a certain conversion type within the defined biomass supply chain. The spatial component of the database module encompasses the multi-modal transportation network. Also the locations of the biomass production, storage, pre-treatment and conversion facilities are maintained in the spatial component by expanding the non-spatial component with four object types that contain the spatial characteristics (i.e. coordinates, object that actually occurs and location specific attributes) of the operation facilities.

Keywords

Biomass to bioenergy conversion, Logical data model, Logistics, Optimisation, Decision Support System

1 Introduction

Spatial fragmentation of biomass production and discontinuous availability of biomass hamper the start-up of biomass-to-bioenergy conversion plants (Iakovou et al., 2010). As a consequence, supply chain modelling and optimisation have received increasing attention in research associated with biomass and bioenergy systems. Our review of literature published between 1997 and 2011, revealed a diversity of methods developed to address strategic, tactical and operational decisions in biomass-to-bioenergy supply chains (De Meyer et al., submitted). Based on this review, we conceived the architecture of a spatial (& temporal) decision support system (s(t)DSS) that can address the optimisation of the biomass-to-bioenergy supply chain logistics. This encompasses the optimisation of the location of operation facilities and the allocation of biomass from production sites to conversion plants taking into account the full and spatially explicit biomass-to-bioenergy supply chain. In this DSS, three integrated modules are at stake (Fig. 1): (i) a generic and flexible database, (ii) a query tool and (iii) an optimisation tool (De Meyer et al., submitted). The *database* encompasses a spatial and a non-spatial component. The non-spatial component covers the possible types of biomass and the possible techniques for harvest, collection, storage, pre-treatment and conversion with their attributes on the one hand, and their mutual relationships and possible sequences on the other hand. The multi-modal transportation network and the location and characteristics of the effective biomass production, storage, pre-treatment and conversion facilities are maintained in the spatial component of the database.

The *query tool* (developed in a GIS software) will allow the user to organise and pre-process the source data and visualise the results. The *optimisation tool* will combine the typical GIS-based network analysis functions and a mixed integer programming (MILP) model to optimise the location of operation facilities and the allocation of biomass from production to conversion as restricted by the supply chain and the multimodal transportation network defined in the database module.

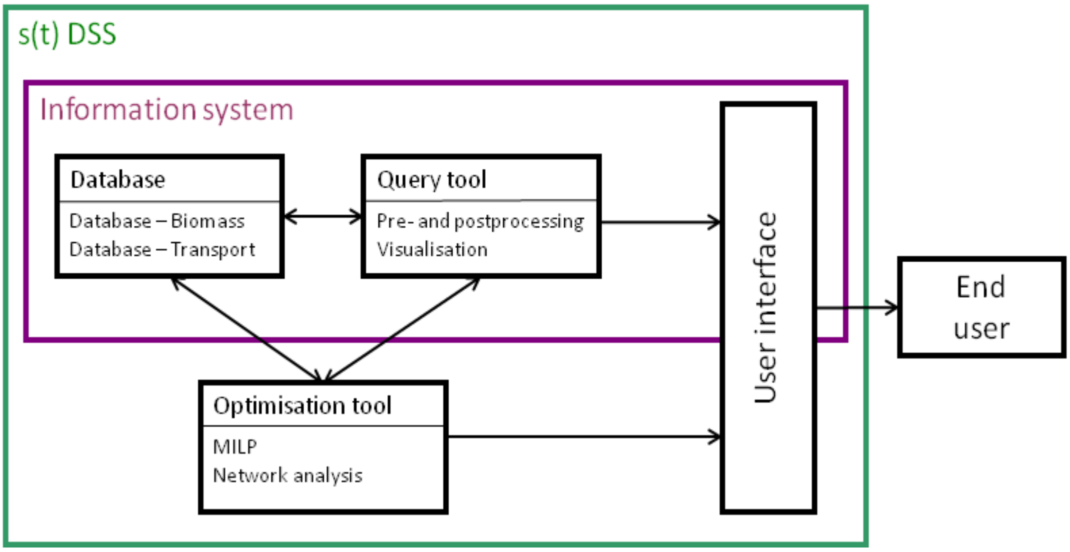

FIGURE 1 Architecture of a decision support system for biomass supply networks (De Meyer et al., submitted)

This paper focuses on the presentation of the non-spatial component of the database module in particular. This is pertinent since our literature review has revealed that so far minor or no attention has been paid to the development of a flexible and generic data model to describe the biomass-to-bio-energy supply chain. The proposed data model is meant to form the template for a functional database for different types of biomass supply chains. This implies that the data model should enable easy addition, deletion or change of objects, attributes and attribute values with minimal redundancy and without compromising the validity of the associations between the various object types.

2 Conceptual description of the biomass-to-bioenergy supply process

Biomass is supplied from a production site to a conversion plant through a sequence or chain of operations which together form a process. The conceptual description of this process is the first step in the data modelling exercise. It encompasses the identification of the types and capacities of the key operations, explicitly attributing spatial (and temporal) characteristics to operation's facilities and transportation links. These operations are considered to be the key entities in the biomass supply process which are required to deal with the typical characteristics of biomass (Iakovou et al., 2010 and Sokhansanj et al., 2006). According to literature, six key entities are distinguished in the biomass-to-bioenergy supply process, i.e. biomass production, harvest, collection, pre-treatment, storage and conversion to bioenergy. These operations are highly interconnected (Allen et al., 1998). This means that upstream decisions affect the later operations in the chain. Also, the choice of biomass conversion technology, size and location will determine the type and sequence of all upstream operations to make sure that the biomass resources arrive at the conversion plant at the correct time, in the correct quantity and in the desired shape, size and quality (Allen et al., 1998) and yielding maximal net energy. Figure 2 presents a flow chart describing the possible operation sequences in a biomass supply chain. This flow chart illustrates that the biomass supply process is very complex covering many different operation sequences and loops. Furthermore, after conversion rest products can be fed back into the supply process and mixing of different product types is frequently applied.

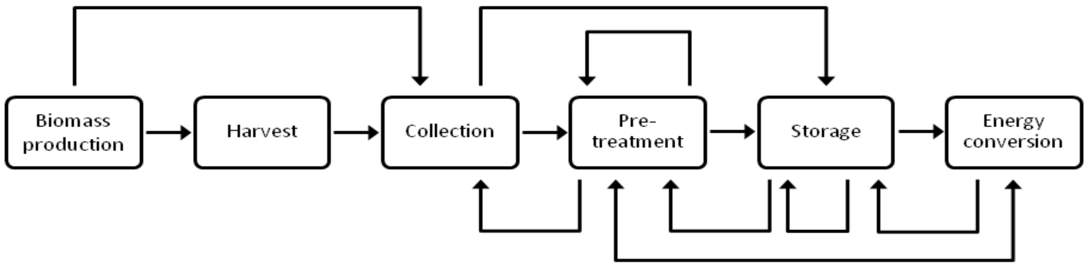

FIGURE 2 Flow chart representing the sequence of operations in the biomass supply chain (De Meyer et al., submitted)

3 Logical data model for the biomass-to-bioenergy supply process

To achieve a DSS that is applicable to different types of biomass supply chains, a generic and flexible data model is required. The genericity implies that the relationships between the object types are defined in a way that the data model can describe all (or most) biomass supply processes. The flexibility of a data model includes that the objects, the attributes and attribute values can be easily changed, deleted or added. Therefore, the core of the data model is non-spatial covering the types of biomass and the techniques for harvest, collection, storage, pre-treatment and conversion with their attributes on the one hand (i.e. key object types), and their mutual relationships and possible sequences on the other hand. To define the possible operation combinations (Fig. 2), many-to-many associations are needed between the six object types (white object types with bold border in figure 3). However, because relational database management systems (RDBMS) only support one-to-many associations, each many-to-many association is converted into a binary association class (i.e. light gray object types) which relates the two object types with two one-to-many associations. Each binary association class defines the possible combinations between the objects of the two original object types and can contain attributes specific for that combination (e.g. the particle size of a biomass type after a particular harvest type). Furthermore, combinations exist in which three key object types are related to one another (i.e. (1) product type – harvesting type – collection type, (2) product type – collection type – pre-treatment type, (3) product type – pre-treatment type – conversion type). De Rore et al. (2005) indicate that the three binary association classes cannot adequately capture all statements about the real world. Therefore, the domain modelling pattern "Three Party Pattern" is introduced which adds a ternary association class (i.e. dark grey object type) to the three binary association classes (De Rore et al., 2005). This ternary association class manages the possible combinations of the binary association classes describing the relationships between the three observed key object types.

So far, the data model, consisting of the six object types, eight binary association classes and three ternary association classes, is able to capture all possible sequences of operations as presented in the flow chart (Fig. 2) but the pre-treatment loop and the conversion loop. To include the pre-treatment loop, three additional object types are introduced. The first object type *pre-treatment sequence* represents the possible pre-treatment sequences, the number of pre-treatments and the total energy input in each sequence. The second object type *pre-treatment step* identifies for each step in a pre-treatment sequence the biomass type for which the sequence is possible, the pre-treatment type executed in that step and the corresponding characteristics of the pre-treated biomass type after that step. Furthermore, the object type *storage after pre-treatment* represents for each step in "pre-treatment steps" which storage types are possible to store the pre-treated biomass. The conversion loop in figure 2 indicates that the rest product from a conversion can be used as input for a following conversion. Analysis of this secondary supply process shows that the same operations are required as used in the primary biomass supply process, i.e. pre-treatment, storage and conversion. This means that extra object types or associations are superfluous and that it suffices to add new product types, pre-treatment types, storage types and conversion types in the corresponding object types according to the secondary conversion chain (e.g. table 1 for the LIHiD biomass-to-bioenergy supply chain).

Also, the possible combinations between the objects are added to the corresponding binary and ternary association classes. Finally, in reality a mix of product types can be used for conversion to bioenergy. Therefore, two attributes, “minimum percentage” and “maximum percentage” are added to the binary association class “product type – conversion type” to restrict the fraction of the product type in the conversion process. This method implies that all product types allowed in a certain conversion type can be mixed.

4 Physical database for the LIHiD biomass-to-bioenergy supply chain in Flanders

The non-spatial data model (Fig. 3) was implemented in the open source RDBMS PostgreSQL 9.1 (www.postgresql.org) resulting in 20 object types which were populated with attribute values with reference to the production of bioenergy from biomass produced by Low-Input High-Diversity (LIHiD) systems. These systems include habitats such as (semi-) natural grasslands, heathlands, swamps, multifunctional forests and small landscape elements (e.g. roadside) requiring minimal inputs and management.

TABLE 1 Objects for the key object types with reference to the LIHiD- biomass-to-bioenergy supply chain including the secondary conversion supply chain

Object type	Object
Biomass type	LIHiD: Subshrub – grass – verge grass – reed – brushwood – log – coppice – residual wood Specific for conversion loop: Digestate – biochar – compost – charcoal
Harvest type	Uniaxial or biaxial sickle mower – uniaxial or biaxial reel mower – uniaxial or biaxial disc mower – uniaxial or biaxial flail mower – brushcutter – excavator harvester – chainsaw
Collection type	Tractor with trailer – mow-load combination – forwarder
Pre-treatment type	LIHiD: chipping – chopping – grinding – pulverising – pelletising – round baling – rectangular baling – ensiling – artificial drying, natural drying – litter removal Specific for conversion loop: Separator – crushing – sifting
Storage type	Container – pile – tower silo – bunker silo – shelter – hangar – manure silo
Conversion type	LIHiD: Pyrolysis – gasification – combustion – anaerobe digestion – composting Specific for conversion loop: Soil fertilizer – soil amendment

The implemented PostgreSQL-database supports a wide range of SQL-queries. An example of a simple query is: “Which harvesting types can be applied to verge grass?” (Answer: uniaxial or biaxial sickle mower, uniaxial or biaxial flail mower, brushcutter). Of course, the objective of this non-spatial data model is to answer more advanced query types covering the complete biomass supply process like “Which operation sequences are allowed when a small scale combustion installation is available?” or “Which operation sequences are allowed when verge grass and brushwood are available?”. Since the answers to such questions encompass tens of records, it is not possible to include them all in this paper. However, to indicate the possibilities of the data model, table 2 presents 5 records (out of 6392) of the query answering the question “Which operation sequences are allowed when verge grass or brushwood are available?”.

TABLE 2 Some resulting records for the question: “Which operation sequences are allowed when verge grass or brushwood are available?”

Biomass	Harvest	Collect	Pre-treatment(s)	Storage	Pre-treatment(s)	Conversion	Pre-treatment(s)
Verge grass	Uni sickle	Trailer	Removal litter + Natural dry + Rect bale	Shelter	Grinding	Digestion	-
Verge grass	Bi flail	Mow-load	Removal litter + Chop	Tower silo	-	Digestion	-
Verge grass	Brushcut	Trailer	Removal litter + Natural dry + Rect bale	Pile	Chop + Art dry	Digestion	Grind
Brushwood	Uni flail	Trailer	-	Hangar	Chip + Art dry	Pyrolysis	Pulverisation
Brushwood	Bi flail	Mow-load	Chip	Hangar	Art dry + Grind + Pellet	Combustion	-

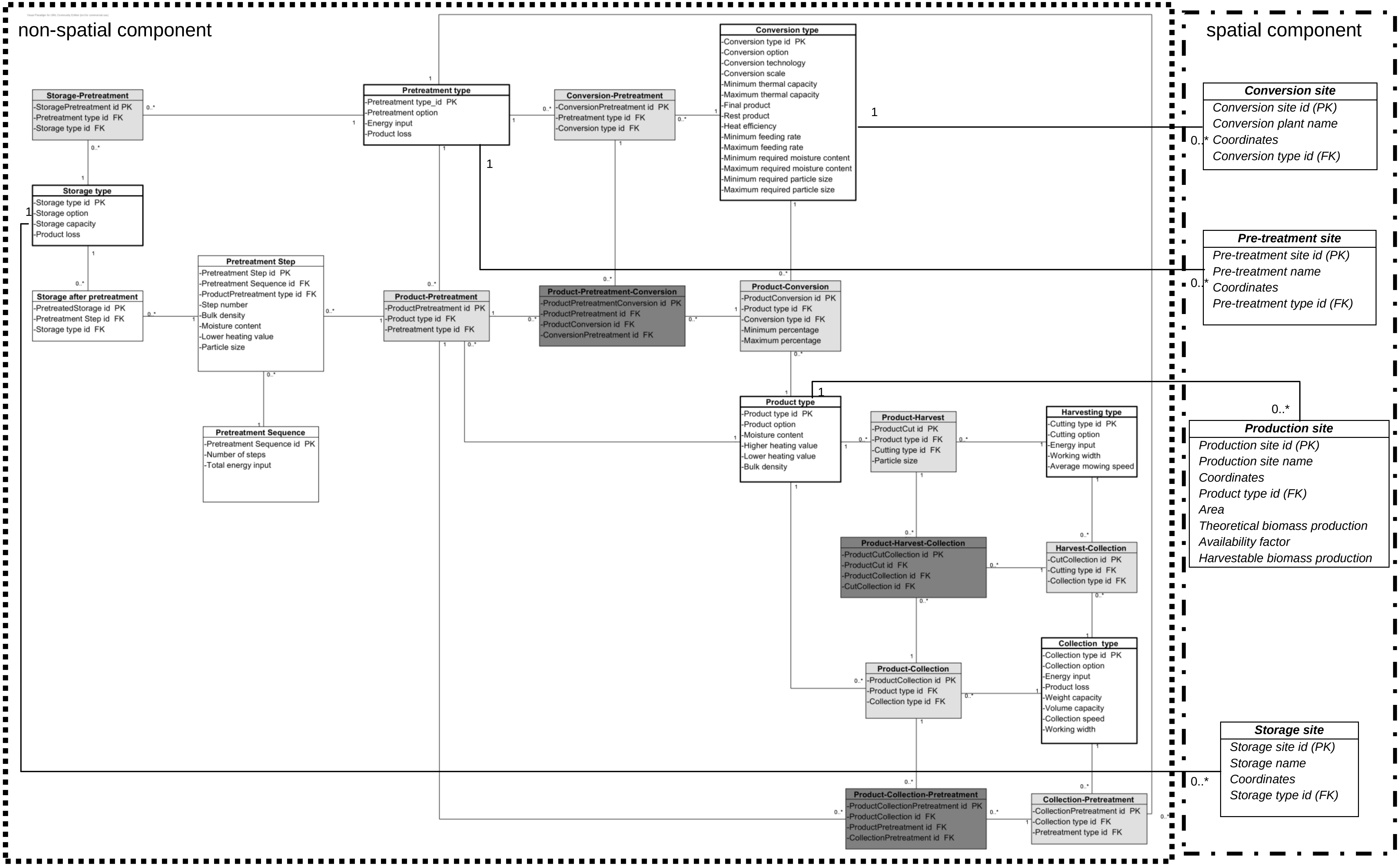

FIGURE 3 Generic logical data model for biomass-to-bioenergy supply chains (PK = primary key, FK = foreign key)

5 Conclusion

An in-depth analysis of the biomass-to-bioenergy supply process has lead to the identification of the key object types (i.e. biomass production, harvest, collection, pre-treatment, storage and conversion) and the associations between these object types. According to this conceptual description, a non-spatial data model covering the possible object types with their attributes on the one hand, and their mutual associations and possible sequences on the other hand was presented. To adequately capture all statements about the real world, the data model makes use of the "Three Party Pattern" (De Rore et al., 2005) in which a ternary association class is added to the three binary association classes. This allows to capture potential interferences between the different associations (De Rore et al., 2005). Furthermore, pre-treatment loops, conversion loops and mixing of product types are included, allowing the development of queries to determine the possible operation sequences within the defined biomass supply chain.

The described non-spatial data model is the template for the non-spatial part of the database module of an envisioned DSS addressing the optimisation of biomass-to-bioenergy supply chain logistics. It covers the possible operation sequences in the supply chains. This non spatial part will be extended with a spatial component encompassing the multi-modal transportation network and the location of the operation facilities. This latter extension requires the addition of four spatial object types (production site, pre-treatment site, storage site and conversion site) (Fig. 3). These object types contain the geospatial coordinates, objects and characteristics of the facilities that do actually occur. The non-spatial data model was implemented in the RDBMS PostgreSQL 9.1 to solve a variety of use cases illustrating the complexity of the biomass supply chain and testing the robustness of the data model.

In the proposed data model limited provision was made to allow the conversion of mixtures of pre-treated and unpre-treated biomass types. Such mixtures have characteristics which deviate from those of the pure product types and which are dependent upon the proportions of the mixed components. On the one hand, it is assumed that product types allowed for a certain conversion type can be mixed with whatever other such product type at the condition that its fraction in the mixture is within a specified minimum and maximum. On the other hand, the determination of the effective mixture proportions is left to a mixed integer linear programming algorithm (MILP) to be included in the optimisation module of the envisioned stDSS.

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7 References

Allen, J., Browne, M., Hunter, A., Boyd, J. & Palmer, H. (1998). Logistics management and costs of biomass fuel supply. International Journal Of Physical Distribution & Logistics, 28, 463-477.

De Meyer, A., Cattrysse, D. & Van Orshoven, J. (submitted). Optimisation methods for strategic biomass supply network design and planning: A literature review. Biomass and Bioenergy.

De Rore, L., Snoeck, M. & Dedene, G. (2005). Domain modelling pattern: 'Three-party pattern'. 10th European Conference on Pattern Languages of Programs, 689 - 702.

Iakovou, E., Karagiannidis, A., Vlachos, D., Toka, A & Malamakis, A. (2010). Waste biomass-to-energy supply chain management: a critical synthesis. Waste Management, 30, 1860 – 1870.

Sokhansanj, S., Kumar, A. & Turhollow, A. (2006). Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). Biomass and Bioenergy, 30, 838-847.