Identification of Optimal Biomass Utilization – Characteristics and Challenges

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Abstract

Interlinked biomass supply chains can be considered as a loose coupling of independent, distributed players. By means of loose (and therefore flexibly alterable) coupling, a regional network of (basically) small players is formed that offers an extensible portfolio of processes, which can be used in variable combinations. Superior sustainability objectives allow for considering energy efficiency, ecological rucksack and other higher-level objectives. If these superior objectives are taken into account simultaneously during network formation, the problem of assigning limited resources to utilization processes in a global optimal way arises. This work-in-progress paper will introduce the preliminary work on an adaptive and resilient system that is able to identify sustainable biomass utilization networks in an unsupervised way. The paper will focus on the model used and point out the requirements for possible algorithms used for optimization of these networks under sustainability objectives.

1 Introduction

Kamm, Kamm, Gruber and Kromus define biomass on the basis of an US program as "any organic matter that is available on a renewable or recurring basis (excluding old grown timber), including dedicated energy crops and trees, agricultural food and feed crop residues, aquatic plants, wood and wood residues, animal wastes, and other waste materials" (cf. Kamm et al. 2010, page 13). In the Renewables Directive (2009/28/EC, article 2 (e)) it is stated that biomass "means the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste".

Biomass can be used in many different ways, obviously as a source for food and feed, but also as a source for pharmaceuticals or biobased products like biomaterials, biochemicals or fuels and energy. Figure 1 depicts some products build on (different kinds of) biomass and their relation.

Since biomass is utilized in many ways, there exists a competition of the players on the market. In addition, biomass is a scarce commodity; of course it is renewable, but crop area and the rates of growth are limited. As a result, intelligent management strategies and supporting information technologies are required for linking multiple alternatives of utilization as well as alternative paths in order to produce (multiple) products and energy (directly used or stored) at the same time. Additionally, different options of biomass utilization have to be assessed in order to define the optimal ones according to the sustainability objectives, what in turn asks for algorithmic support. These aspects can be covered with a cascading usage of biomass. Figure 2 depicts the concept of cascading according to (Arnold et al. 2009). Arnold et al. (2009, page 18) define the cascading usage of biomass (or just cascading) as the sequential use of biogenic feedstock for material and energetic applications.

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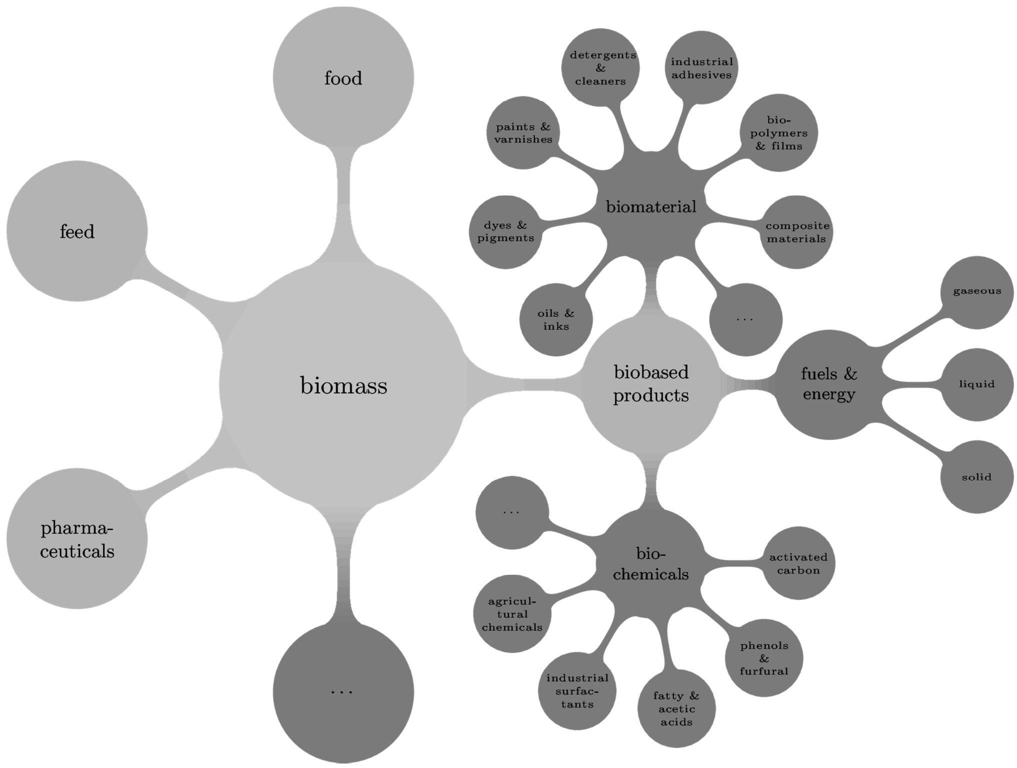

Figure 1
Product groups that originate from biomass organized as a mindmap (based on the work of Kamm et al. (2010))

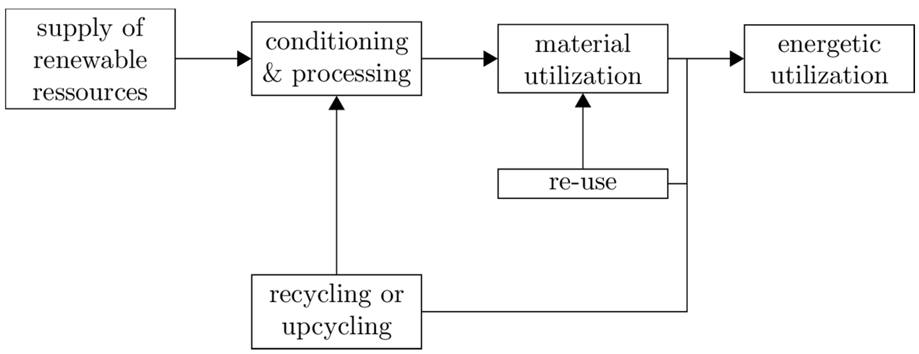

Figure 2
Cascading of biomass – a schematic (as defined in Arnold et al. (2009))

Straw could serve as a minimal real-world example: After harvesting seeds or grain (and removing the chaff) straw is left on the fields. From an isolated perspective the leftover straw offers two competing opportunities of utilization:

1. Plowing the straw and using it as fertilizer.
2. Combusting the straw and using the resulting heat, what is financially advantageous.

When taking into account the idea of cascading usage, a more valuable usage would be combusting the straw *and* using the remaining residue (ash) as fertilizer.

This example as well as similar examples are manageable without further technical support. More complex real-world examples which include a greater variety of resources and alternative and cascading usages ask for an algorithmic support. The overall objective is to build up an optimal network of tempo-spatial fluctuating resources and processes. Optimality refers to the best utilization of available resources. All matches (between a resource and a process) that make up the network will be chosen according to sustainability aspects; according to upcoming unknown events (disturbances, etc.) only the robust ones will be used. In a real world example the matches would be realized by transports.

This paper has a strong focus on the modeling of the use case of “identification of optimal biomass utilization”. The characteristics of the major players involved and what technique seems (not) to be able to handle the problem are discussed in section 2. Section 3 focusses on the specifics and challenges of biomass, as the field of application. These characteristics are the basis of requirements for the optimization task. Section 4 delivers insight into the next steps of this ongoing research.

2 The Field of Application: Characteristics of Supply, Demand and Matches

Given is a set of independent participants having equal rights. Each participant may be a provider or consumer (or both at the same time), offering or requesting biomass, a service (like shipment), or processing steps. The objective is to find an optimal interconnected network of collaborating participants for better (at best optimal) utilization of the available biomass sources. The resulting network must not be valid only once as a static formation, but permanently. That means optimality has to be defined over time. Moreover, an optimal solution has to be a solution that is sustainable and that solves a multi-criteria problem.

Each process is characterized by a function, which maps an input (from a set of required inputs) to a set of resulting outputs. These outputs can be used as input to other processes. The network problem of formation and running can be illustrated by looking at a toy example: There may be given two inputs In_1 and In_3 as well as three processes P_1, P_2, and P_3. The possible networks and, particularly, the optimal network are a priori unknown. One possible cross-linking is depicted in Figure 3. It is obvious, that the depicted cross-linking cannot be built from close to scratch based on the given set of available entities. As a first step only In_1 and P_1 (producing an intermediate called $Inter_1$) as well as In_3 and P_3 can be directly connected. Until In_2 is not available, the existing chains can’t be linked and the desired outputs Out_1 and Out_2 are not produced.

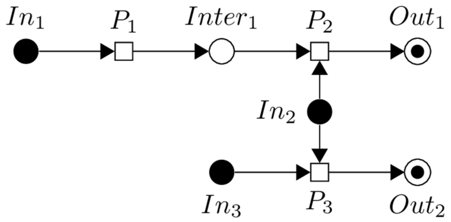

Figure 3
A toy example of cross-linked players

Generally, the sets of available resources (also called inputs or goods) and processes are a priori known; we are asking for the optimal network. The optimal linkage emerges from the distributed connecting of matching entities, in which some requirements have to be respected: An edge is only allowed if both nodes can be matched according to their types and matched semantically. Matching types are resources and processes as well as processes and outputs. Once processes are connected in series (daisy-chained), like P_1 and P_2 inside the chain $In_1, P_1, Inter_1, P_2, Out_1$ depicted in Figure 3, edges from processes and intermediates and vice versa are also allowed. However, each chain has to start with an input and has to end with an output.

As stated above, for our case we assume that all resources and processes are a priori known in general and the optimal cross-linking is asked. That means, all matches are usually unknown at the beginning. But it is also possible to consider pre-defined networks or parts of an already existing network – maybe some already established consumer-producer-relations have to be considered. If some parts (of a network) are provided in advance, these parts have to be considered in a special way: It is assumed that such an a priori known (part of a) network has to be preserved or improved. Such entities are not allowed to be deleted suddenly, just fading away is allowed – like the evaporation of pheromone trails in ant colony optimization algorithms. But only iff a new setting is determined, that presents an equal or better solution for all affected players.

As soon as the network build-up starts, all nodes and maybe some a priori edges (= predefined partial networks) are known. During the process of building the network new nodes or edges can arrive or already known or used nodes or edges can fail. That means that building the network is an online problem, since the data set (availability of nodes and edges) changes during runtime and the build-up can't just take place once but rather continuously.

From the networks point of view, each resource and each process is represented as a node, whereas matches determine the linkage of the network. Possible subtypes of a resource are input, intermediate or output. Each resource node must be of exactly one type, but the type can change at runtime. A node of type output can become an intermediate, once the output serves as an input to another process. In addition, each used process must be connected to at least one input and must at least provide one output, in which three special cases have been identified:

1. Lossless storage: Such a process does not modify the input; the generated output is equal in each attribute to the consumed input. The perfect storage of a good may serve as an example.
2. Transformation and usage of resources: Most of the processes will consume one or more inputs and produce a new output. Since not all processes and/or resources can be modeled and specified in all detail there will be faults at accounting level.
3. Transshipment: Such a process is considered to be an extension to the both cases explained above. It extends the lossless storage case by only changing the value of the good's position attribute. As an extension to the second case, the spatial position of the output gets changed.

Generally, all available nodes are independent of each other, are equally privileged and are unknown to each other, but unique identifiable. As an exception it is also possible to specify dependencies between nodes, sequences of nodes or priorities, hence it becomes possible to specify unchangeable parts of an a priori known network.

When looking at an edge, an edge indicates that both involved nodes can be matched. Suitability of two nodes can be determined based on the type of biomass provided and in demand, quality, price, and spatial or temporal requirements, just to mention a few. Each edge connects supply and demand. If all used edges are written as an adjacency matrix, the resulting matrix is likely to be sparse, because not all suppliers are qualified for meeting all demands. However, partial delivery is permitted as well as the procurement of demand from several suppliers. In our case, all edges are directed because sequences have to be followed and edges are later on instantiated by real transportation routes. Routing is done by sophisticated and mainstream algorithms like in (Rapp et al. 2011).

The identification of appropriate edges is based on finding possible matches on the attribute level and benchmarking all edges until finding the best one. Some hard and soft constraints have to be considered:

- Hard constraints: Such constraints determine the validity of a solution. That means all requirements must be met by a valid solution. The right type of the nodes considered, a matching on attribute level may serve as an example here. If a part-solution (edge) is valid, it does not mean that it will exist or be used in the resulting network.

- Soft constraints: This kind of constrains decide on the quality of a solution. That means if not only the hard but also the soft constraints are fulfilled, the quality of a solution is high. A higher quality increases the likelihood that the solution becomes part of the network. The quality itself is determined by using the direct and indirect costs of each edge.

When looking at Figure 3 and talking about inputs, processes and outputs, it suggests itself to think about Petri nets. Petri nets are directed, bipartite graphs $N = (P, T, F)$ with a set of places P (resources), a set of transitions T (processes), and a set of edges called flow relations $F \subseteq (P \times T) \cup (T \times P)$. Each place can contain tokens – in our use case tokens are a concrete instance of a specific biomass object (in terms of an object-oriented language). For an in-depth discussion of Petri nets see for example (Reisig 2010).

At first sight, material flow models (Möller 1998) seemed to be promising when talking about material and energy flows organized as a Petri net. Material flow models are based on Petri nets, but differ in some principal points. Such a network is defined as above ($N = (P, T, F)$), with P taken as stock, T interpreted as the conversion of materials and/or energy, and each edge as an element of F. Any edge consumes and/or produces tokens. In material flow networks, quantities are used instead of tokens. Technically, transitions don't fire in material flow network, thus networks are not event-based (Schmidt/Klein 2002), they do not consider single events.

Such networks focus on observing quantities for period-oriented reporting, like life-cycle assessment. Such strong orientation on the quantities ignores the majority of available information. Since firing is substituted by a given initial marking for a period's begin and the final marking is calculated based on the transitions, information and conclusions can only be derived for a full period. In addition, knowledge must be available a priori, in order to provide the initial marking.

Basically, Petri nets appear to be very appropriate to represent (and depict) the discussed network. When thinking of some biomass characteristics, like quantity and quality or the distribution and availability of biomass, they change over time – but continuously, not in discrete steps. In contrast, characteristics with a range of discrete values exist also. This asks for an approach of modeling and simulating hybrid systems. Such an approach based on Petri nets was introduced by Wieting (1998). He calls his approach HyNetze, an abbreviation of the German term hybride höhere Netze (hybrid high-level nets, HyNets). His approach combines high-level Petri nets for the discrete parts of the system, an object-oriented extension to the standard token concept, and differential equations and algebraic equations for the specification of the continuous behavior.

Each overall objective (building a closed region, weak-point analysis, location planning, etc.) influences what is considered to be optimal; sometimes multiple objectives have to be combined. In addition to the right (optimization) algorithm and the right parameterizing, the underlying model needs to handle discrete and continuous aspects appropriately. HyNets can be used for the complete process of:

1. Definition: Defining available participants (resources and processes), edges to be used right from the start, and events. All definitions can be made via a graphical user interface using the syntax and semantics of HyNets or in batch mode via suitable formatted specifications (file) including the domain, range and/or a distribution for each attribute or parameter. The graphical interface is quite useful for first-time-modelers or small examples.
2. Network build-up and network updates: If no predefined network is available, an initial network needs to be established. This job is done by sophisticated algorithms. The initial network is extended gradually by the algorithm selected by the modeler. Technically, HyNets won't be used 'inside' algorithms directly due to performance issues, but all algorithms are able to visualize their

current calculations as HyNets to enable the modeler to view the steps needed when identifying the optimal biomass utilization according to the chosen optimization objective.

3. Evaluation: The evaluation of the current network is available at any time, for the initial or current network and the unlinked elements as well as after termination. The presentation will focus on the preselected evaluation criteria, but also address some common parameters (for example on graph level).

3 Specifics and Challenges of the Application Field

For the rest of the paper we will discuss the major use case aspects of the optimization problem. While finding an optimal network structure, the following specific characteristics have to be considered:

- spatial fluctuation,
- temporal fluctuation,
- fluctuation of participants, and
- universalism of biomass.

3.1 Spatial Fluctuation

Normally, the (biomass) production is highly distributed, so large and patched geographical areas have to be considered. Additionally, biomass from residues and waste is even more scattered and – typically – this sources are scarcely and unevenly distributed. Often, this demands the combination of the yields of several distributed patches to achieve a sufficient (or requested) amount. This means, that sometimes a request can only be satisfied by several independent (maybe competing) suppliers. In addition, the materials that have to be handled are quite often very voluminous and due to (high) transportation costs the distances of transports are limited.

3.2 Temporal Fluctuation

The availability of biomass is affected by several uncertain seasonal fluctuations. The variations of the seasonality at least spans into three dimensions: quantity, time and quality. Another source of seasonality on longer terms, that has an effect on the temporal variation of geographical distribution are crop rotation techniques. If biomass imports are ignored, the one or maybe few availability windows of crops do have to be taken into account. If preprocessing (like separating seeds or grain from straw) is applied on site, the resulting resources become geographically coupled and timely constrained (but not necessarily coupled).

3.3 Fluctuation of Participants

An optimally interconnected network is made-up of multiple nodes (producers and consumers) connected by links (transshipment). Due to the fact that this network should be active and evolve over time, joining or leaving nodes have to be considered multiple times. It’s quite likely that the determined network will exhibit hysteresis – this effect needs to be handled in a proper way. Of course, the network is not allowed to oscillate - in contrast it must be resilient.

3.4 Universalism of Biomass

Because of its diversity, biomass is a multiply usable resource on the one hand, but also requires flexible processes on the other. Sometimes different forms of (maybe the same or part of) biomass have a different applicability to specific utilization processes. Additionally, the specific utilization processes could be competitively. Nevertheless, the links that make up a better interconnected network will be part of a cross-linked and cascading utilization.

3.5 The Optimal Network

In our case we are looking for an optimally interconnected network, where optimality means:

- A stable (peer-to-peer like) system, which itself is balanced and is not oscillating.
- A sustainable utilization of biomass that satisfies environmental, social and economic aspects.
- A Pareto optimal linkage of participating players, where no link between players can be changed without increasing the costs for at least one stakeholder.
- Being optimal over time and not only at one point in time (snapshot) by adapting to changes without supervision in a distributed environment. These changes may include joining or leaving players, new and unforeseen upcoming events, seasonal as well as strategic and durable changes of structures and flows (quantity, quality and direction).

In order to solve the problem of finding an optimal interconnected network, different possible links have to be scrutinized. Depending on the degree of dynamics within the system the question for appropriate trading counterparts (suitable links) has to be answered multiple times, taking into account the materials quality, timing, type and subtype, amount, location and applicability as well as volume and transporting capacities, just to name a few. The amount of information needed for decision making asks for an unambiguous description of the resources (services and process steps) to ensure that one has the right resource of appropriate quality in the right place at the right time.

4 Summary & Next Steps

The technical aspects of biomass exploitation on the one hand and biomass production on the other are currently put forward trough research and development projects, whereas cascades of use increasingly gain in importance. A so far scarcely discussed issue is adequate dynamic structures for optimal regional networks. Taking into account, that various forms of biomass (particularly including residue) have a different sustainability for different usage opportunities and furthermore are available temporal and spatial distributed, the dynamic problem of finding the global optimal matching between limited resources and consuming processes arises.

The current practice of manually searching for trading partners neither allows for analyzing existing trade relations nor identifying alternative network linkage and design options, because the focus is not on the communities vantage but on sole participants, this prevents the establishment of sustainable interconnected networks for biomass flows. As stated above, algorithmic support enables us to handle highly dynamic (regional) biomass networks organized in a sustainable, cooperative way.

Since the overall objective is to build up an optimal network of tempo-spatial fluctuating resources and processes, there are a couple of tasks to accomplish. First of all, the model must be formalized completely and robust algorithms appropriate to build up and maintain such a network have to be found and implemented. As a further step stone, some metrics and indicators have to be identified or developed in order to assess and evaluate optimality. In addition, further metrics and indicators have to be identified for assessing and interpreting the results.

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